Physical Rock Weathering along the Victoria Land Coast, Antarctica

A thesis

submitted in fulfilment
of the requirements for the degree

of

Doctor of Philosophy
in the
University of Canterbury

by

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University of Canterbury
2006

ABSTRACT

The purpose of this research was to investigate the physical weathering of rock along the Victoria Land Coast, Antarctica. It was designed to contribute to the Latitudinal Gradient Project, a joint initiative between the New Zealand, Italian and United States Antarctic Programmes. The Latitudinal Gradient Project aims to improve our understanding of the ecosystems of the Dry Valleys and ice-free areas of the Ross Sea Region and, by using latitude as a proxy measure, identify how they might be affected by future climate change.

The approach taken for this research was to use information on rock (from one rock group) temperature and moisture conditions gathered from three field locations to inform laboratory simulations. The laboratory simulations would then be used to investigate the weathering of small rock blocks and aggregates. Two temperature cycles approximating those experienced during summer and spring/autumn were identified and simulations undertaken in a specially adapted freezer. Three levels of moisture were applied: no moisture, half saturation and full saturation. Results of the laboratory simulations indicated that although rocks responded in different ways to different processes, granular disintegration took place even in the absence of additional moisture and did not require crossings of the 0 ^{O}C isotherm, nor were high levels of moisture required for across zero temperature cycling to produce weathering effects.

A model that related weathering to latitude was developed and changes in climate explored. It was found that the weathering effect of summer and spring/autumn cycles was different and depended on rock characteristics rather than latitude. Increasing the ratio of summer to spring/autumn temperature cycles by 10% indicated that weathering could decrease or remain the same depending on the particular rock. Changes in temperature were found to be more important than changes in moisture. A weathering index that related local climate and rock properties to weathering was also developed and this highlighted the difficulties of using laboratory results to predict field rates of weathering.

There were some surprising results from the field, including the presence of much more moisture on the surface of the rock, primarily from blowing snow, than had been predicted for this dry environment. This occurred even in the presence of negative rock surface temperatures. In addition, winter rock surface temperatures can fluctuate up to 25 ^{O}C, getting as 'warm' as -10 ^{O}C. Macro-climate and changes in air temperature in response to foehn and katabatic winds were the drivers for these fluctuations.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter explains the rationale for the research, including an introduction to the importance of rock weathering, the significance of moisture in rock weathering studies and the relevance of weathering in the context of climate change (Section 1.2). Section 1.3 details the aims of the research and outlines the approach taken and Section 1.4 describes the structure of the rest of the thesis.

1.2 WEATHERING, MOISTURE AND CLIMATE CHANGE

Goudie (1994, p.556) describes weathering as "….one of the most important geomorphological and pedological processes" and Brady (1990 p.23) states that

> *'The influence of weathering, the chemical and physical breakdown of particles, is evident everywhere. Nothing escapes it. It breaks up rocks and minerals, modifies or destroys their physical and chemical characteristics ………'*

It is weathering that initially breaks up the rock, or reduces it sufficiently in strength, to enable the processes of erosion to occur. In addition, rock weathering influences the development of terrestrial ecosystems by providing some of the materials and nutrients for soil formation. Rock weathering also plays a vital role in the rock cycle by breaking up and/or altering igneous and metamorphic rocks to form sedimentary ones as well as providing a sink for carbon dioxide.

Several studies into rock weathering in cold climates have stressed the important role of moisture (e.g., Humlum, 1992; Odegard & Sollid, 1993; Sass, 2005). Hall & Hall (1996 p.365) noted that the "Temporal and spatial variability of rock moisture in cold regions are recognized as major factors affecting the nature and extent of rock weathering" (Hall 1986a, 1988a, 1991, 1992; Thorn 1988, 1992) and Yoshikawa et al., (2000) concluded that it was moisture availability that was the most important control on frost shattering in the Ellsworth Mountains, Antarctica. In a recent review of rock weathering research Hall et al., (2002) went so far as to state that it was moisture availability, not temperature that limited weathering in cold regions. The unique properties of water together with its wide distribution are the reasons that moisture plays such a dominant role in most weathering processes where it can act either as a solvent, an active component in a chemical reaction or as the source of a physical force (Bland & Rolls, 1998).

Most research on moisture movement in rocks has been undertaken in the laboratory (e.g., Prick 1995) and with one or two exceptions (e.g., Humlum, 1992; Yoshikawa et al. 2000; Sass, 2004), field studies have tended to concentrate on how spatial and temporal access to water influences the weathering processes that operate (e.g., Hall, 1993a) or when most weathering occurred (e.g., Fahey & Lefebure, 1988). Apart from the laboratory work of Prick (1997), no attempts to quantify the influence of changing moisture availability on weathering rates have been made. With some exceptions (e.g., Humlum, 1992; Yoshikawa et al., 2000; Elliott, 2004; Sass, 2004, 2005), the availability of moisture to the surface of the rock has received little attention. Consequently, little is known about the spatial and temporal variability of moisture reaching the surface of the rock nor how much or to what depth this moisture may penetrate below the surface.

Global Climate Models (GCMs) predict that the effects of any future climate change will be greatest at the poles, particularly in winter (Callaghan et al., 1999). Although, the effect of climate change may be less in the Antarctic than in the Arctic, this may not apply to coastal areas (Maxwell, 1998). Any change in climate is likely to manifest itself as increased temperatures (perhaps by as much as $2.5^{O}C$ by 2050) and precipitation, although how climate change will affect the latter is less clear (Fitzharris, 1996). However, Fountain et al., (1999) expected that even very small variations in temperature and precipitation, because they can lead to extreme variations in the hydrologic regime, would have a potentially great impact in the McMurdo Dry Valleys (Figure 1.1).

The ice-free areas of Antarctica are recognised as unique ecosystems (Campbell & Claridge, 2000) with soils being one of the most important components of the ecosystem (Campbell et al., 1998). Antarctic soils are described as “particularly fragile” (Campbell et al., 1997 p.45) and as being least well developed in coastal areas (Bockheim, 2002). Soil processes operate very slowly in Antarctica (Campbell et al.,

1998) and the low species diversity and absence of certain functional groups means that the loss or gain of even one species due to environmental change can have a profound effect on the ecosystem (Walton et al., 1997).

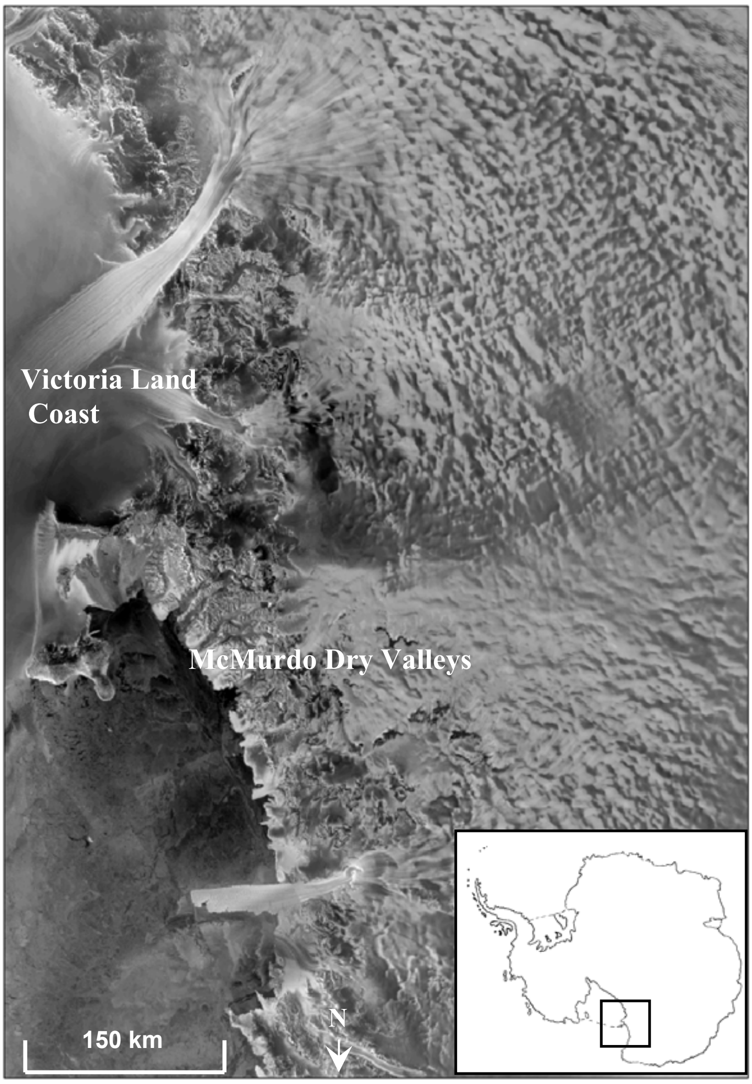


Figure 1.1: Location of McMurdo Dry Valleys and Victoria Land Coast

As well as direct impacts on the soils and ecosystems, increased temperatures and precipitation may have indirect effects. For example, changes in temperature will alter the depth of the active layer (Bolter, 1996), shift the freeze-thaw line and affect temperature variation below the surface (because of the release of latent heat associated with potentially greater moisture) (Campbell et al., 1997). Consequently, it is important to understand how any change in temperature and/or precipitation might affect weathering rates, particularly if there is a change in freeze-thaw regime. The *rate* at which rock weathering occurs is important because it determines how quickly or slowly the soil and landscape develop. Current rates in the Arctic and Antarctic are very slow, for example 0.3 mm a^{-1} in Svalbard (Jahn, 1976) or between 0.2 and 1 x 10^{-3} mm a^{-1} in the Dry Valleys (Summerfield et al., 1999), similar to those found by André (1995) for crystalline rocks in Scandinavian Lapland.

The Latitudinal Gradient Project (LGP), a joint initiative between the New Zealand, Italian and United States Antarctic Programmes, was established in order to better understand the potential impacts of climate change in the Dry Valleys and the ice free coastal areas of the Ross Sea Region (Peterson & Howard-Williams, 2001). In particular, it aims to:

- Improve understanding of the complex ecosystems that exist along the Victoria Land Coast (Figure 1.1); and,
- Determine the effects of environmental change on these ecosystems

Essentially the LGP uses changes in latitude as a proxy for changes in climate and this research was designed to contribute to the LGP by providing information on rock weathering in this environment and the likely effect that changes in temperature and precipitation might have on this.

1.3 Research Aims and Approach

The importance of rock weathering, particularly in fragile environments such as Antarctica, the lack of knowledge of the role of moisture in weathering processes and the development of the Latitudinal Gradient Project were driving factors in developing the primary objective of this research:

> *To investigate physical rock weathering along the Victoria Land Coast, specifically by examining the role that moisture and temperature conditions play in determining the rate that rocks break down in these environments*.

A model that would relate moisture and temperature conditions to weathering rate and enable predictions of how this rate might change under future climate change scenarios was also to be developed. With one or two notable exceptions (e.g., Hallet, 1983; Walder & Hallet, 1985; Matsuoka, 1991), very few rock weathering studies have attempted to develop models that will predict weathering rates.

The overall approach was a combination of fieldwork and laboratory work combined with a statistical framework (Figure 1.2). Fieldwork, including collection of data on rock temperatures and moisture conditions, was to provide the information needed to determine the environmental cycles necessary for laboratory simulations to be undertaken and field sites were to be chosen to provide both a coastal/inland as well as a latitudinal perspective. The simulations would then determine the effects that different temperature and moisture conditions would have on the weathering of small rock blocks and aggregates. The laboratory experiment would be developed so that individual processes could be identified. To reduce the potential influence that differences in the properties of the rocks might have one rock group, Granite Harbour Intrusives, would be investigated. The statistical approach (a combination of analysis of variance and repeated measures analysis), coupled with the laboratory design would enable the individual effects of temperature or moisture as well as any interaction between the two to be determined. The information on weathering rates and the processes deemed responsible for them would then enable a model to be developed that would relate weathering rate to moisture and temperature conditions.

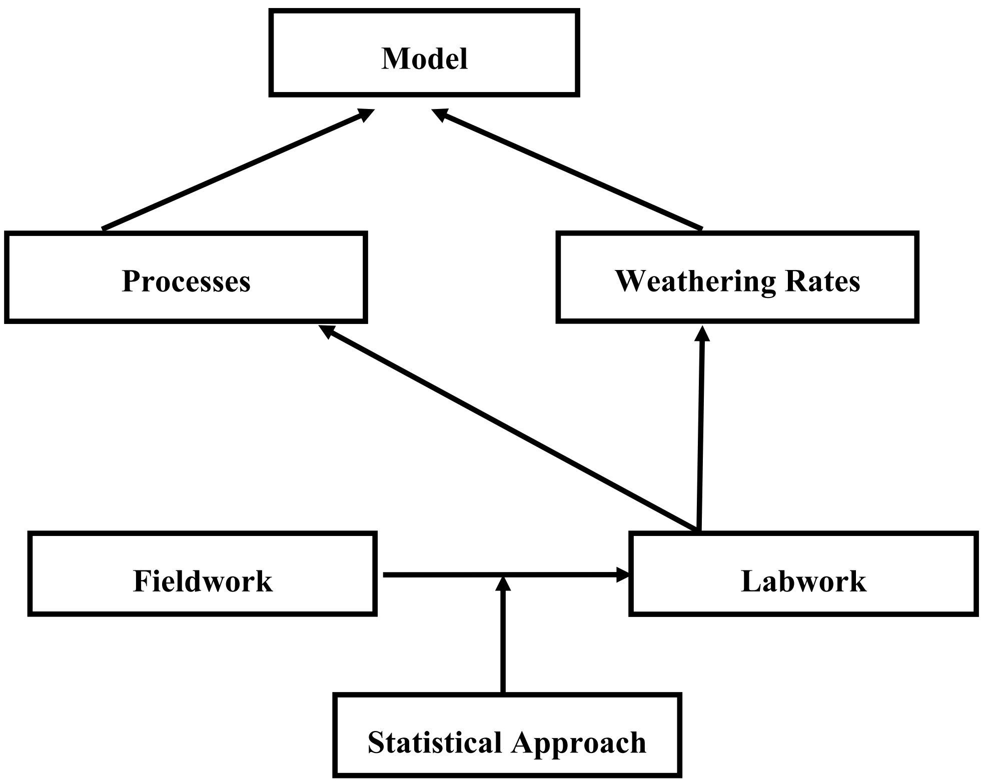


Figure 1.2: Approach to undertaking research showing the relationship between the field and laboratory work and the model

The individual research questions were developed following a review of the debate in the literature about whether it is temperature or moisture that is most important in driving weathering rates (e.g. Hall et al., 2002); the lack of knowledge on the availability and influence of moisture on weathering rates and processes (e.g. Fahey & Lefebure, 1988; Humlum, 1992; Sass, 2005) and the limited agreement on which processes operate in these environments (Hall et al., 2002). The Latitudinal Gradient Project provided the framework within which to undertake the research and offered an opportunity to contribute to the increased understanding of potential future climate change in this environment.

Four questions were then identified:

1. For a specific rock group, what is the total weathering rate at each of the field sites?
2. What processes are operating in this environment and what are the weathering rates for specific processes?
3. Are there temperature and/or moisture regimes for which physical weathering is most effective?
4. Is there a relationship between weathering rate and latitude, as determined by moisture and temperature conditions, along the Victoria Land Coast?

The research was focussed on the small scale, both in terms of the gathering of data in the field (i.e. the micro-environment) as well as in the laboratory (the use of small rock blocks and aggregates). In addition, because the timescales under investigation were short, only weathering by physical processes was considered (Section 2.6).

1.4 THESIS STRUCTURE

This thesis has eight chapters and the first (this chapter) describes the importance of weathering as well as the rationale for undertaking the research, focussing on the role of moisture in particular. The relevance of the research in the wider context of climate change is also explained.

Chapter 2 defines rock weathering and gives a description of the rock weathering system. A brief summary of knowledge on rates of weathering in the Arctic and Antarctic together with the different approaches to studying weathering are also provided. The types of weathering (physical, chemical and biological) as well as the different processes that operate are outlined, including frost, salt and insolation weathering, as well as wetting and drying. The chapter finishes with a review of recent research into rock weathering in cold climates, and in Antarctica in particular.

Chapter 3 describes the field sites and presents a rationale for their inclusion. The methodologies used to measure the rock temperatures and moisture contents as well as the climatic variables are provided and the key results for each presented.

Chapter 4 provides a description of the important features of the rocks under investigation and Chapter 5 focuses on the laboratory component of the research and includes a description of the experimental design as well as the individual experimental procedures undertaken. The response of the rock samples from the field to the different temperature and moisture conditions is given in Chapter 6. This chapter also outlines the important aspects of the results for weathering research generally as well as for this research in particular. Specifically, it discusses the results in terms of the first three research questions.

Chapter 7 addresses the fourth research question and describes the model and uses it to consider the potential effects of climate change on weathering. Chapter 8 summarises the conclusions, limitations of the research and areas for future investigation.

Appendix 1 provides further details of the experimental procedures undertaken and Appendix 2 contains the datalogger programmes used in the field. The programme used to control the freezer is provided in Appendix 3. Two papers were published during the course of this research. These are referred to in the relevant sections and are included as appendices to the thesis (Appendix 4).

CHAPTER 2

BACKGROUND

2.1 INTRODUCTION

This chapter provides the background for the thesis and gives an overview of the relevant aspects of rock weathering and rock weathering research. Section 2.2 provides a definition of rock weathering and Section 2.3 describes the rock weathering system together with the important factors to be considered when undertaking rock weathering research. Section 2.4 is a summary of the important characteristics of rocks and their properties, with a particular emphasis on granite. The concept of rock strength is discussed and methods of measuring it outlined in 2.4.2. The different ways that rocks respond to the forces placed upon them are considered in 2.4.3. The difference between weathering rate and intensity together with a summary of methods of measurement and estimates of rates determined in a number of cold environment studies are the subject of Section 2.5. The processes of physical rock weathering are then described, including frost weathering (2.6.2), insolation weathering (2.6.3), wetting and drying (2.6.4) and salt weathering (2.6.5). Section 2.6 focuses on the individual processes and the mechanisms deemed responsible for their operation. It does not attempt to summarise the various arguments for and against the proposed mechanism, unless the underlying tenets of a process are challenged. Where relevant these are considered in Section 2.7, which also provides a review of research into rock weathering in cold climates.

2.2 DEFINITION OF ROCK WEATHERING

The concept of rock weathering as the 'preparation of debris for erosion' was first introduced by the geologists Yates and Phillips in the 1830s (Yatsu, 1988). Several books (or chapters in books) and papers subsequently appeared in the geological literature but Yatsu (1988) believed that it was not until the mid 20th Century with the advent of X-ray diffraction techniques that geomorphologists really became interested in weathering. However, Nordberg and Turkington (2004 p.427) argued that it was the popularity of process-based studies in geomorphology generally in the 1960s and 1970s that brought about "….concentrated and explicit" attention to weathering research. Either way research into rock weathering by geomorphologists has been relatively recent, although soil scientists have been interested for much longer (e.g., Merrill, 1897).

Rock weathering is generally understood to occur at or near the surface of the earth in response to the changed environmental conditions that rocks experience once they are exposed to the atmosphere. It is an *in situ* process and does not require the help of external agents such as wind, ice or flowing water. However, encapsulating this idea in a concise definition has proved difficult and Yatsu (1988) summarised the various attempts. He finally settled on a rephrased (and translated) version of a definition by Correns (1939, p.119);

> *'Weathering is the alteration of rock or minerals* in situ*, at or near the surface of the earth and under the conditions that prevail there'*

The deep alteration of rock by sedimentation and metamorphism was excluded from his definition of weathering.

More recent definitions are similar. For example, Ollier (1984 p.1) described weathering as "…the breakdown and alteration of materials near the earth's surface to products that are more in equilibrium with newly imposed physico-chemical conditions". However, Dixon (2004 p.1108) defined weathering in terms of the processes that are "…collectively responsible for the breakdown of materials at or near the Earth's surface". Paton et al., (1995 p.15) use the term epimorphism to describe the way minerals formed deep within the earth change on exposure to near surface conditions and weathering becomes "…..that part of epimorphism dealing with the breakdown of minerals". Regardless of definition, Nordberg and Turkington (2004 p.421) concluded that "Rock weathering therefore involves the release of compounds into solution, creation of new mineral products and breakdown of rock into smaller pieces". It is the breakdown of rock into smaller pieces that is the focus of this research.

2.3 The Rock Weathering System

A systems approach to geomorphology in general and rock weathering in particular helps to identify the range of variables that need to be considered and the potential interactions between them. Ahnert (1998) described three broad types of geomorphological system: static, process and process-response. Each has a particular set of forms and form characteristics, type of material and material characteristics as well as processes and process characteristics. Static systems are essentially a snapshot in time of a set of forms and materials whereas process systems also include the time factor. A more complete picture is given by consideration of process-response systems which describe the relationship between the static components and the response components and take into account not only the effect of processes on the form or materials but also the influence of the form and materials on the processes i.e. they include the idea of feedback.

The complexity of the rock weathering system and in particular the difficulty of investigating and/or disentangling the interactions between processes has been noted by several authors (e.g. Warke, 2001; Goudie, 2000), and Hall (1992) attempted to show the relationship between freeze-thaw (or frost weathering), the other physical weathering processes and the properties of the rock diagrammatically (Hall 1992; Figure 5.3). This indicated that not only can processes be interrelated but individual rock characteristics can influence more than one process.

Robinson and Williams (1994 p.xv) stated that the principal variables controlling weathering have long been recognised as "the composition and structure of the parent rock, the nature of the climate and the length of time over which weathering has operated". More recently it was recognised that it was the climate at the grain surface, in particular the temperature and moisture conditions that were the important factors in weathering studies (e.g. Warke, 2000). The scale at which processes of weathering operate must also be considered (Whalley & Turkington, 2001; Viles, 2001).

Hill and Rosenbaum (1998 p.85) described rock weathering as a "dynamic, multi-factorial system comprising the interactions between the rock mass itself, the agents of weathering and the environmental conditions." They identified the following controlling factors in a rock weathering system:

1. Climate
2. Biological activity
3. Mineralogy
4. Texture
5. Discontinuities
6. Permeability

7. Geomorphology
8. Time

Hall (1992) developed a flow chart of the six factors he identified as important for physical weathering studies (Hall, 1992; Figure 5.3):

1. Rock albedo
2. Rock temperature
3. The temperature gradient in the rock
4. Rock moisture content
5. Moisture chemistry
6. Rock strength

These could be summarised as rock microclimate (1-5) and rock properties (6). Smith and Warke (1997) included the influence of inherited change to the materials in their discussion of the factors that influence weathering.

2.4 ROCKS AND ROCK PROPERTIES

2.4.1 Introduction

The importance of the rock type and its properties in weathering studies has been recognised for some time (e.g. McGreevy, 1981) and in order to have an understanding of the processes of weathering it is necessary to have a basic grasp of rock mechanics as well as knowledge of the properties of the rock type being studied. The focus of this research was on cold climate physical weathering at a small scale and so the primary interest was in those processes and the properties of the rock that may influence this. Consequently, the discussion that follows concerns those aspects of rocks and rock mechanics that shed some light on the granular disintegration and/or small scale cracking or fracturing of rock. Where appropriate it provides information on granitic rocks in particular.

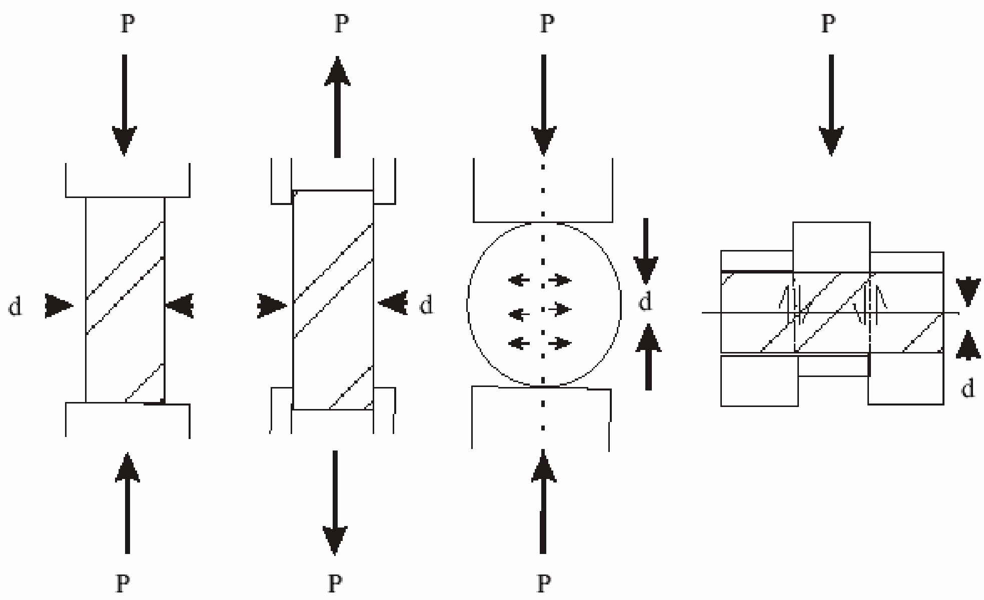
There are several definitions of rock depending on the perspective and purpose of the person undertaking the investigation. Whether it be for example, engineer, geologist or geomorphologist (Selby, 1985), and it is the geomorphological definition of rock that has been adopted here. Rock therefore is “an intact material of mineral grains cemented together; it is a hard elastic substance which does not significantly soften on immersion in water" (Selby, 1985 p.172). Minerals are defined as “a naturally occurring substance that has a characteristic chemical composition and, in general, a crystalline structure" (Oxford Dictionary of Science, 1999). They can be bonded in three different ways: ionic, covalent and, under particular conditions, hydrogen. Ionic bonds are formed by the transfer of electrons, for example in the formation of sodium chloride one electron is transferred from a sodium atom to a chlorine atom (changing the charge of both). Covalent bonding on the other hand occurs when pairs of electrons are shared (rather than transferred) between atoms such as when the dihydrogen molecule (H_2) with two electrons (one from each hydrogen atom) bonds with an oxygen atom (which has 6 electrons) to form the water molecule (H_2O). The third type of bond of interest in rock weathering discussions is where the hydrogen atom is covalently bonded to another atom with strong electron attracting powers such as oxygen. The oxygen atom attracts the pair of electrons in the oxygen-hydrogen bond towards itself leaving the positive nucleus of the hydrogen atoms exposed. This is then attracted to a lone pair of electrons on an oxygen atom in an adjacent water molecule forming a hydrogen bond (Bland & Rolls, 1998).

Three broad groups of rock are recognised: igneous, metamorphic and sedimentary depending on how and where they were formed. Ninety five per cent of the Earth's crust is made up of igneous rock (Ollier, 1984) with granite, at 15%, being the third most common rock type at the surface (Leopold et al., 1964). Practically all igneous rocks are composed of silicate minerals; silicon-oxygen tetrahedra that are linked in various ways. There are six structural classes with the ones of particular interest to this research being the phyllosilicates such as biotite which have a sheet structure, and the tektosilicates, which include quartz and feldspar, that have a three-dimensional network (Beavis, 1985). Igneous rocks also contain one or more other common elements such as potassium, calcium, iron or magnesium (Strahler & Strahler, 1992).

Attewell & Farmer (1976) distinguish between 'intact' and 'massive' rock and define 'intact' to mean small scale rock material used in laboratory tests and 'massive' to describe rock as it is found in the field i.e. modified by the presence of joints, fissures, bedding planes etc. When investigating weathering of rock it is important to specify which type of rock is being considered since this affects how the rocks respond to the different weathering processes. Several authors have highlighted the difference in weathering response displayed by field and laboratory investigations as a consequence of this e.g., Matsuoka (2001a).

2.4.2 Rock Strength

The susceptibility of a particular rock to weathering can be summarised in the concept of rock strength. Hall (1987) stated that rock break up will only occur when the forces acting on the rock are greater than the strength of the rock. However, there is more than one definition of strength. Selby (1985, p.172) defined strength as “the ability of a material to resist deformation by tensile, shear, or compressive stresses”, where stress is the force per unit area of cross section and is measured in Nm^{-2} or Pa. The difference between tensile, shear and compressive strength depends on the direction of the applied force (Figure 2.1). Attewell and Farmer (1976 p.183) are more specific in their definition and state that the strength of an *intact* rock material is “usually defined as the maximum force or combination of forces per unit area (that is, the active stresses) which the material can support”. Middleton and Wilcock (1994 p.109) include the idea of permanent change in the rock so that strength is the “stress necessary to produce significant permanent deformation”. This implies that there is some condition of deformation that equates to failure and the stress producing that failure is defined as the strength of the rock.



Compression	Direct Tensile	Indirect Tensile	Shear
$S_C = \frac{4P}{\Pi d^2}$	$S_T = \frac{4P}{\Pi d^2}$	$S_T = \frac{2P}{\Pi dL}$	$S_S = \frac{2P}{\Pi d^2}$

Where P = pressure or force; d = diameter; L = length

Figure 2.1: Force directions for uniaxial strength (S) measurement. Redrawn from Attewell & Farmer (1976 p.185)

Figure 2.1 illustrates the case of uniaxial (i.e., in one direction) strength. However, in reality it is more likely that stresses will occur in a number of directions (i.e., biaxially at the surface or triaxially at depth). C*ompressive* strength (as measured on an unconfined cylindrical test specimen) is easier to measure than either tensile or shear strength and is often used to express the strength of a material (Attewell & Farmer, 1976). However, in terms of weathering and the processes described earlier the tensile strength, or the ability of a rock (or its particles) to be prised apart, is most important. Although difficult to measure, tensile strength is usually of the order of up to 8 times less than compressive strength in rocks (Middleton & Wilcock, 1994, p.131).

Attewell & Farmer (1976 p.186-189) identify a number of intrinsic characteristics of rock that will affect its strength.

(i) Porosity and Density

The total binding force of the rock depends on the total area of contact between individual particles and this is inversely proportional to the amount of pore space i.e., the lower the porosity (volume of voids as a % of total volume) the greater the binding force or strength of the rock.

(ii) Grain size and shape

Intergranular contact area increases with decreasing average grain size and angularity strengthening the rock. However, grain boundaries can be potential areas of weakness where cracks may either exist or be initiated and the length of a grain boundary may influence the strength of a rock. For example, it is known that edge dislocations within a crystal structure may pile up at a grain boundary generating and/or increasing a crack. The longer the boundary, the more rapidly existing cracks will propagate, increasing the likelihood of failure at low stresses. Therefore grain size as well as shape can determine the strength at which rocks fail, even when they are mineralogically similar.

(iii) Anisotropy

If a rock has a preferred orientation of its mineral grains then the strength of the rock can be affected by the direction of the stress on it i.e., whether this is perpendicular or parallel to the preferred orientation. This is not usually the case for granite.

(iv) Mineralogy

The tensile strength of a granitic rock is inversely proportional to its quartz content (Merriam et al., 1970). In other words, the greater the percentage of quartz in granite then the lower its tensile strength becomes. This is due to textural differences where high quartz rocks, composed of equi-dimensional grains have little crystal intergrowth or interlocking compared to low quartz content rocks consisting of interlocking lattices and prisms. Although, Price (1960, cited in Attewell & Farmer, 1976) found the opposite for compressive strength in sandstones.

(v) Moisture Content

Attewell & Farmer (1976), mean this in the sense that significant quantities of water in the pore spaces of a rock reduce its strength and they give several possible explanations for this.

Bland & Rolls (1998) provide a useful distinction between the inherent properties of the rock (i.e., those related to the constituents and structure of the material) and the mechanical which describes the way in which the rock responds to changes in stress (Table 2.1).

Table 2.1: Inherent and mechanical properties of rock

Inherent	Mechanical
1. Texture: including grain size and its relation to porosity, surface area, permeability and capillarity 2. Discontinuities at various scales 3. Water content, measured by natural moisture content, water absorption capacity, saturation coefficient	1. Compressive strength 2. Shear strength 3. Tensile strength 4. Elasticity

Source: Bland & Rolls (1998)

Rock strength can be measured directly or indirectly. Direct measurement is usually undertaken in the laboratory and often involves destroying the samples e.g., point load test. Indirect methods such as the use of a Schmidt hammer or sonic device are described in Section 2.5.

2.4.3 Deformation of Rocks

Rocks deform, or strain, in various ways in response to the stresses placed upon them. These can be the result of internal earth processes such as earth movement or the cooling of formerly molten rock or by the processes of weathering such as temperature change or the conversion of liquid water to ice. Failure occurs when the rock becomes permanently deformed or fractured into two or more parts and brittle materials are defined as those where their resistance to tensional separation is less than their resistance to shear or sliding. Ductile materials are defined as those where their resistance to separation is greater than their resistance to sliding i.e. where failure takes place by flow rather than fracture (Vutukuri et al., 1974).

Strain in a rock specimen can be axial or lateral: axial strain (ε) is the proportional change in the length of a specimen and lateral strain the proportional change in breadth. Poisson's ratio (υ) is the ratio of lateral strain ($\acute{\varepsilon}$) over axial strain (ε). Bland & Rolls (1998) identified four types of strain that are relevant to rock weathering studies: elastic strain, brittle failure, fatigue failure and plastic failure.

Elastic strain is any strain that is recoverable once the stress is removed and the elasticity of a rock is measured by the modulus of elasticity or Young's Modulus (E) where:

$$E = r/e \ (Nm^{-2}) \text{ where } r = \text{the applied stress and } e = \text{the consequent strain}$$

It is usually (but not always) constant to the failure point i.e., to the point where the strain is no longer recoverable. The value of E is inversely proportional to the amount of deformation produced by a given stress i.e. it is a measure of a rock's ability to resist deformation. Some rocks may behave elastically when exposed to temperature change and so do not break down.

Brittle failure occurs in some rocks when the stress builds up beyond the elastic limit and the rock experiences sudden catastrophic failure. Experimental results show that the level of failure varies quite considerably within and between rock types and with the type of stress. Although rocks generally show least resistance to tensile stress this may be countered by the constraining effects of surrounding rock. However, the tensile strength of a body of rock may be severely weakened by crack development and, according to Bland & Rolls (1998), a major consequence for weathering is the growth of cracks at various scales which are then exploited by weathering agents. For example, a crack approximately 1/100th of a body's dimension can reduce its tensile strength by $10^2 - 10^3$ times.

Griffiths (1921) introduced the concept of inherent flaws in materials that can then develop into micro-cracks or larger. Stress concentrations occur at the advancing crack tip and cracks tend to propagate in a direction perpendicular to that of the maximum tensile stress. Cracks propagate when the tensile strength of the material is less than or equal to the tensile stress where the latter is proportional to the inverse of the square root of the crack length. In other words, the tensile strength of a completely brittle material is determined by the largest crack existing prior to loading. Crack propagation can then be either stable or unstable i.e., even when the stress is stopped crack propagation continues. Unstable crack propagation occurs when the relationship between the length of the crack and the applied stress ceases to exist and other factors such as crack growth velocity take over.

Fatigue failure may occur when a stress is repeatedly applied, even though the magnitude of each stress event is below the yield strength of the material i.e., the material reaches its fatigue limit. For hard rocks the compressive fatigue limit is approximately 70 to 75% of the initial compressive strength whereas it is of the order of 50-60% for tensile stress and 30% for alternating tensional and compressive stresses. Fatigue failure in hard rocks probably occurs by micro-crack extension as strain energy is stored (Bland & Rolls, 1998). Attewell & Farmer (1976) differentiate between short term and long term deformation behaviour of an intact rock material. Long-term deformation occurs when the rock is subjected to a sustained or cyclic sub-failure stress.

Finally, plastic failure is a non-recoverable strain that occurs by slow deformation rather than sudden failure and is typical of less brittle rocks and materials such as some clay minerals when they absorb water and expand. The internal changes that creep involves may alter a rock's resistance to weathering.

Although rocks are usually considered to be brittle materials they may also be ductile or even be transitional between brittle and ductile. The reaction to deformation depends on a variety of factors such as the confining pressure, temperature, rate of strain or the presence and nature of interstitial solutions (Vutukuri et al., 1974). Consequently, this makes the determination of the strength of a material difficult to estimate in practice (Middleton & Wilcock, 1994).

2.4.4 Granite

Granite is a coarse-grained plutonic igneous rock that has been formed by the crystallization of magma that has cooled slowly under the surface of the earth. It is composed predominantly of quartz, feldspars and mica (often biotite) with traces of other minerals such as hornblende (Press & Siever, 1986). It is classified as an acid igneous rock where the silica content is two thirds or more and quartz is relatively abundant (Beavis, 1985) but the pressures and temperatures under which it is formed influence these (Press & Siever, 1986). Some of its basic physical and thermal characteristics are given in Table 2.2.

Table 2.2: Properties of granite

Strength[1] (MPa)			Porosity[2] (%)	Bulk Density[2] (Mgm^{-3})	Thermal Conductivity[3] ($Wm^{-1}K^{-1}$)
Compressive	**Tensile**	**Shear**			
100-250	7-25	14-50	0.5-1.5	2.6-2.9	3.05

[1] Attewell & Farmer (1976; p185); [2] Attewell & Farmer (1976; p187); [3] Mean value, Warke (2000; p89) citing Cermak & Rybach (1982)

Quartz is a tektosilicate mineral meaning that its structure is a three-dimensional network where the 4 oxygen atoms are shared (Figure 2.2). It has a rigid structure and a coefficient of linear thermal expansion of 9 x 10^{-6} K^{-1} parallel to the c-axis but 14 x 10^{-6} K^{-1} normal to the c-axis (Bland & Rolls, 1998). Although quartz does crack at low temperatures (French & Guglielmin, 2000) it is usually a residual weathering material.

Figure 2.2: Quartz crystal, Source: Department of Geology and Planetary Science, University of Pittsburgh

Feldspar can be potassium rich (orthoclase) or sodium/calcium rich (plagioclase). These are also tektosilicates sharing four oxygen atoms but, unlike quartz, have two cleavage planes that intersect at right angles (Figure 2.3). Feldspar is most susceptible to weathering by chemical processes.

Figure 2.3: Feldspar block showing almost perpendicular cleavage planes, Source: Department of Geology and Planetary Science, University of Pittsburgh

Biotite is a phyllosilicate meaning it is formed of sheets of silica tetrahedra and shares three oxygen atoms. It has a layered structure of silicate sheets that are weakly bonded together by layers of potassium ions and has a perfect cleavage in one direction (Figure 2.4). This structure makes biotite more readily weathered by physical processes.

Figure 2.4: Biotite crystal, Source: Department of Geology and Planetary Science, University of Pittsburgh

2.5 WEATHERING RATES AND INTENSITIES

How much a rock has weathered can be described in one of two ways: intensity or rate. The intensity of weathering is a measure of the amount or quantity of alteration of the rock from its initial state at a point in time. Weathering rate on the other hand is defined as the amount of change per unit time and consequently requires not only an estimate of the amount of weathering that has taken place but also over what period of time it has occurred. The latter usually requires material to be dated, which is never straightforward (Bland & Rolls, 1998).

Weathering intensity can be described visually. For example, Selby (1980) developed a scale of mass weathering grades that classified rock as unweathered fresh; or slightly, moderately, highly, or completely weathered to a residual soil depending on how it looked. More quantitative approaches include the use of the Schmidt hammer, which measures rock hardness (e.g., Hall, 1987), and a sonic test which measures the velocity of ultrasonic waves (e.g., Fahey & Gowan, 1979; Hall, 1988b), as proxies for rock strength.

The Schmidt hammer measures the rebound distance (R) of a controlled blow by a known mass impact on a rock surface (Ericson, 2004). Variations in R (over space and time) give a proxy measure of the mechanical strength of the rock. This is a simple and easily carried out approach but can be affected by surface roughness or differences in rock type (Aydin & Basu, 2005). However, provided care is taken in its use, it is still deemed to be a very valuable technique in the field (e.g., Ballantyne et al., 1998; Winkler, 2005). Sumner & Nel (2002) found that moisture affected the results (by decreasing the R-value) but this was least for low porosity rocks and was based on high degrees of saturation. In addition, empirical equations have been developed that relate rebound value to Young's Modulus (Section 2.4.3), uniaxial strength and dry density (e.g. Katz et al., 2000).

The velocity of ultrasonic waves is much slower in air than in rock material. As the rock deteriorates changes in porosity are reflected in changes in ultrasonic velocity. Methods are also available to convert ultrasonic velocity to Young's Modulus (Fahey & Gowan, 1979).

Other methods consider the degree of alteration of the chemical composition of the rock either absolutely or relatively. For instance, the 'benchmark mineral' method compares the change in the proportion of a specific mineral such as Alumina in the parent material with that of the rock material under investigation. The percentages of the other minerals are then adjusted accordingly (Bland & Rolls, 1998). More recently, physical changes inside the rock have been identified through thin section analysis (French & Guglielmin, 2000).

Both field and laboratory methods have been used to quantify weathering rates. These have included weighing debris produced by rockfall in the field (e.g., Fahey & Lefebure, 1988) as well as measuring the disintegration of rock samples in simulated conditions in the laboratory (e.g., Hall, 1986b). Micro-erosion meters have also been used to determine weathering rates in the field (e.g., Spate & Burgess, 1995). Other field approaches have included the study of naturally weathered material or measuring the solute or suspended sediment output of a catchment. Issues with these methods include a shortage of relevant dates against which to measure change or difficulties in measuring actual amounts of solutes being released due to storage in the system. It may also be difficult to convert the weathering rate to one of surface lowering (Bland & Rolls, 1998). Laboratory simulations suffer from a number of simplification issues such as limited time or the use of unrealistic inputs such as salt concentrations, moisture availability etc., (Goudie, 2000) and Bland & Rolls (1998) noted that weathering rates measured in the field were one to three orders of magnitude slower than those measured in the laboratory.

A more conceptual and mathematical approach to determine weathering rates was developed by Pope et al. (1995) for boundary layer weathering. This related weathering rate to a function of a wide range of factors, both known and unknown. Trudgill (2000) produced a more simplified version that described weathering as the sum of the effects of the processes involved.

Eggleton (1986 p.21), in a discussion on chemical weathering, noted that weathering rate will "depend on the mechanism whereby the weathering agents break the bonds between atoms of a crystal." This in turn was affected by "the bond strength, the chemical activity of the agents and the crystal structure." He described the rate limiting factors as diffusion avenues such as cleavage cracks and fractures which increased the surface area of crystal open to attack and lattice defects. However, it was important to also recognise that the effect of these on weathering rate depended on whether they had been filled by alteration products. In summary the rate of weathering of a mineral in a given environment depended on (1) the existence of initial diffusion avenues and (2) the rate of growth of new stable minerals. Rapid growth blocked the diffusion channels and resulted in a slow rate of weathering whereas a slow rate of growth gave time for some elements to diffuse out, leaving channels open and resulting in a faster rate of weathering.

Colman & Dethier (1986) noted that determining physical weathering rates was even more difficult than that of chemical weathering and in polar areas Ugolini (1986) noted that estimates of weathering rates were largely qualitative and mainly in relation to soils. He identified a number of factors in polar areas that were either favourable or unfavourable to weathering. Factors against were mainly related to the low temperatures which affected the rate of any chemical reactions as well as the state of the water which, except for the carbonates, hampered dissolution reactions of the minerals. Low temperatures also influenced the mobility of water and solutes or suspended matter when frozen as well as the growth or decomposition of biological components. Factors that favoured weathering in polar environments included the long duration of sunlight in summer, an abundance of UV radiation, sparse vegetation cover, unobstructed land surfaces, rapid temperature excursions, steep temperature gradients and numerous cycles of wetting and drying as well as freezing and thawing, strong winds and the accumulation of soluble salts, although he did also note the paucity of liquid water and the limited extent of ice-free areas in Antarctica.

Studies that provide estimates of weathering rates in cold climates and in Antarctica in particular are rare. A number described rock wall retreat in alpine areas and Barsch (1993) provided a summary of these ranging from 2.5 mm a^{-1} for rock glacier permafrost in the Alps (Barsch, 1977 in, Barsch, 1993) to between 0.01 and 0.1 x 10^{-3} mm a^{-1} in the central Yukon (citing Gray, 1970). Jahn (1976) found rates of 0.3 mm a^{-1} over a 50 year period in the sub-polar desert of Longyeardalen in Svalbard. More recently, André (2002) examined glacially scoured rock surfaces on roche moutonnée in an 8 km^2 area of northern Scandinavia and estimated weathering rates were 0.2 x 10^{-3} mm a^{-1} for homogeneous crystalline rocks regardless of acidity and grain size but 1 x 10^{-3} mm a^{-1} for those that were biotite rich.

Summerfield et al. (1999) determined rates of between 0.2 and 1 x 10^{-3} mm a^{-1} in the Dry Valleys of Victoria Land, Antarctica. However, Spate & Burgess (1995) found much higher estimates of surface lowering in the Larsemann and Vestfold Hills of Princess Elizabeth Land, East Antarctica: 15 x 10^{-3} mm a^{-1} and 22 x 10^{-3} mm a^{-1} respectively. Several Antarctic studies were concerned with abrasion by wind and Malin (1985) found maximum annual rates of 0.25 mm for basalt and 1.00 mm for non-welded volcanic tuff (citing Malin, 1984) but 0.03 mm for basalt and 0.50 mm for tuff in a one year exposure. These results were much lower than wind tunnel experiments (Miotke, 1982a) by up to a factor of 100 times.

2.6 PROCESSES OF PHYSICAL WEATHERING

2.6.1 Introduction

Rock weathering processes are generally classified as being physical, chemical or biological (Selby, 1993). Some authors, for example Yatsu (1988) prefer to classify the processes of biological weathering as either physical (e.g. breaking of rocks by plant roots) or chemical (e.g. alteration of minerals by plant acids). Physical weathering processes include the effects of alternate and repeated freezing and thawing (frost weathering); heating and cooling (insolation weathering); wetting and drying (hydration) and the growth of salt crystals from solution, thermal expansion or hydration (salt weathering) (Selby, 1993). Insolation weathering includes rock breakdown due to 'thermal fatigue' as a result of repeated heating and cooling regardless of temperature range or gradient as well as 'thermal shock' due to very rapid changes in temperature. Yatsu (1988) gave an in depth discussion of all the rock weathering processes and Elliott (2003) gave an overview of the state of research into each of these processes in relation to cold climate weathering and Antarctica in particular.

Minerals remain largely unaltered by physical (mechanical) weathering which simply breaks the rock up into smaller components. Chemical weathering on the other hand produces alteration or decomposition of the rock mineral (Figure 2.5).

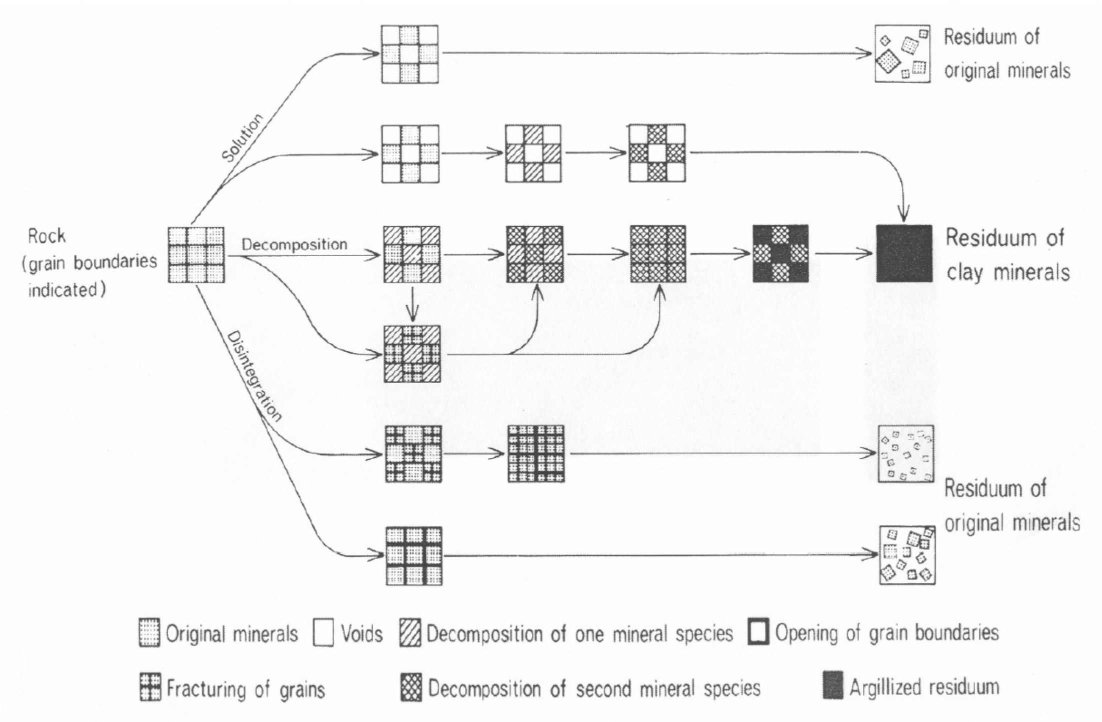


Figure 2.5: Stages in the weathering of rock material under the effect of various processes (from Selby, 1993 p127)

Goudie (1994) classified the various weathering processes into those of disintegration and decomposition (Table 2.3) and, although this can aid our understanding it is a simplified approach that can mask the potential interactions of processes (e.g. Hall, 1992; Whalley & Turkington, 2001). For example, there has been a significant amount of research into the possible synergies of salt and frost weathering, although results were inconclusive (Fahey, 1985) or sometimes contradictory (Williams & Robinson, 1981; McGreevy, 1982). Goudie (1994) pointed out that mechanical weathering could greatly aid chemical weathering by exposing additional surfaces to chemical attack.

Table 2.3: Classification of weathering processes according to Goudie (1994)

Process Type	Description
Processes of disintegration (physical or mechanical)	Crystallization Processes Salt weathering Frost weathering Temperature Change Processes Insolation weathering Fire Expansion of dirt in cracks Wetting and Drying Pressure and release of erosion by overburden Organic processes e.g. by root wedging
Processes of decomposition (chemical weathering)	Hydration & hydrolysis Oxidation and reduction Solution and carbonation Chelation Biological chemical changes

2.6.2 Frost Weathering

Frost weathering has probably been the most intensively researched of the potential physical weathering processes in cold climates. Nevertheless, considerable debate continues about its distribution (e.g. Fahey, 1973), its effectiveness in producing material (e.g. Wiman, 1963) and the actual mechanism that operates (e.g. Walder & Hallet, 1985). Its efficacy is attributed to the pressures built up in rocks by the expansion of water as it freezes in joints, cracks or bedding planes (resulting in macrogelivation) or intergranular pores or microcracks (resulting in microgelivation). Macrogelivation produces clast size material whereas microgelivation produces fine material including small rock flakes, sand, silt and particles up to 32 mm in size (Ballantyne & Harris, 1994). Five potential frost weathering mechanisms are described by McGreevy (1981): volumetric expansion, capillary theory, crystallisation pressure of ice, ordered water hypothesis and hydraulic pressure hypothesis. However, the ordered water hypothesis is not necessarily associated with frost weathering and so is more appropriately discussed in Section 2.6.4. The volumetric expansion and capillary theories as well as the ordered water hypothesis are also reviewed by Ballantyne and Harris (1994). Matsuoka (1990a) introduced the adsorption theory as an advance on the capillary theory.

2.6.2.1 Hydraulic pressure hypothesis

The hydraulic pressure hypothesis is based on the idea that an advancing ice front creates an hydraulic pressure in a critically saturated rock. This assumes that the water content near the surface of the specimen is at or near total saturation and is higher than the average water content of the specimen as a whole. Once freezing begins the water at the surface freezes and forms a seal displacing the remaining free water into the specimen. This in turn creates a pressure as well as a reaction to the pressure (Powers, 1945).

2.6.2.2 Crystalline pressure of ice

Frost weathering due to the crystallisation pressure of ice i.e. the linear force of growing ice crystals is based on the work of Evans (1970) who developed the idea after considering rock shattering by salt crystallisation. Provided rates of freezing are slow (so that supercooled water can move to zones of crystallisation) and the rock has a permeable texture (to encourage the migration of water) ice crystals will grow in directions in which growth is opposed by external force. However, Bland & Rolls (1998) question whether sufficient pressures can be developed for this process to be truly effective and noted that crystallisation from the melt is required.

2.6.2.3 Volumetric expansion theory

This is the most popular and most commonly quoted mechanism of frost weathering because of the apparent simplicity of the idea. It is based on the work of Bridgman (1912) who showed that water expanded by 9% on freezing and that the resulting pressure is sufficient to crack rocks (207 MPa at -22^{O}C). Repeated freezing and thawing was deemed to result in the disintegration of the rock, although no conclusion has been reached on whether it is the frequency (e.g. Russell, 1943), rate or intensity (e.g. Lautridou & Ozouf, 1982) or type of cycle (e.g. Wiman, 1963) that is the most effective.

Grawe (1936) noted that a wide variety of theoretical pressures for ice had been suggested. These ranged from 150 (approximately 1 MPa; Branson & Tarr, 1935 cited in Grawe, 1936) to 34,000 lbs per square inch (234 MPa) at -22 ^{O}C (Scott, 1932 cited in Grawe, 1936) or even up to 110,000 lbs per square inch (758 MPa; based on Adams, 1928 cited in Grawe, 1936), although he doubted this latter figure.

These pressures are theoretical maxima and require four conditions to be fulfilled *simultaneously* (Grawe, 1936):

1. Water must be confined completely so that it cannot migrate from one point of the rock to another as pressure increases (i.e. it requires a closed system)

2. The system must consist of only one component, water, which initially is present only in the liquid phase

3. The temperature (in the rock) must be -22 ^{O}C

4. The rock confining the water must be strong enough to reach the theoretical pressures (although this seems like a counter argument; provided the rock breaks, weathering has occurred regardless of achieving the maximum pressures indicated)

Difficulties in achieving these conditions were highlighted. For example, Bridgman (1912) found that it was extremely hard to keep liquids confined under high pressure and so it was unlikely that water would remain confined in a rock within the frost zone. However, Battle (1960) suggested two ways that a closed system could effectively be produced: either by ice forming a seal at the crack opening or freezing taking place so rapidly (> 0.1 ^{O}Cmin^{-1}) that when water was supercooled there was no time for the resulting expansion to be compensated by expulsion.

The existence of a single component system is also unlikely since voids usually contain air as well as water. The air can be either free or dissolved in the void water so that a multi-component system containing a gas phase, capable of considerable compression, exists. In addition, once air gets into the voids of a rock, it is not easily displaced and the rock is not likely to become saturated very quickly. Moisture must also be freely available since the breaking up of the rock results from repeated freezing and thawing where the ice acts as a wedge widening the fissure a little more each time a frost occurs and an open system of water would be required (Taber, 1929, 1930). Bridgman (1912) noted that, because the transformation itself sets up a pressure that depresses the freezing point, only a small amount of ice actually forms at 0 ^{O}C under atmospheric pressure. This, together with the release of latent heat as temperature falls, meant that freezing takes place under gradually increasing pressure and Grawe (1936) noted that ice melts when compressed.

The only condition that Grawe (1936) considered would be readily achieved in nature was that of the rock reaching temperatures of -22 ^{O}C which he deemed would occur quite commonly in temperate climates even at low altitudes. However, he also noted that rocks exposed at the surface are under tension, not compression and so the pressures required to crack them may be much less than the supposed maximum pressure.

2.6.2.4 Capillary theory

The capillary theory of frost weathering was developed from the work of Taber (1929, 1930) who investigated frost heaving in soils. He recognised that all soil water did not freeze at the same temperature and so it was possible for water to migrate towards a freezing front where the growing ice crystals could displace the material overlying them and develop into ice lenses. Ice segregation occurred rapidly for particles with an average diameter of less than one micrometre. Water occupying very small voids did not freeze rapidly and so could remain undercooled in the vicinity of the ice crystals. However, the process required high quantities of water initially and slow freezing so that water could remain in its liquid phase in close proximity to the ice. Taber (1950) later extended these ideas to his investigations into the breakdown of limestone along lake shores.

Everett (1961) established that the pressure (p) generated by ice forming in rock pores was proportional by a functional relationship between the radii of the pores (R) and the capillaries (r) of the form: $p \propto \{1/r - 1/R\}$. For a material of a given mechanical strength there would be a critical pore size difference which may lead to frost breakdown. Mellor (1970), through his work on granites, limestones and sandstones, found that, as in soils, considerable amounts of water could remain unfrozen in the presence of ice in rock discontinuities. In addition, the small residual quantities of water that remained unfrozen below -10 ^{O}C were electrically continuous making it possible that they were also hydraulically continuous and hence mobile under potential thermal or hydraulic gradients.

Hallet (1983), Walder & Hallet (1985, 1986) and Hallet et al., (1991) extended the theory by incorporating both the investigations of Gilpin (1979) into the "liquid like" layer between the ice and the substrate in soils and the concept of crack growth in rocks. The segregation ice theory was built on the fact that:

1. Liquid water and ice co-exist at or below 0 ^{O}C
2. At low temperatures water migrates to a freezing front
3. The suction force this creates induces a pressure on the rock material
4. This pressure exploits cracks in the rock so that crack growth occurs, inducing physical weathering

Gilpin (1979) demonstrated that in frozen rock the film of water between the ice and the substrate exerted an attractive or suction force on the water in the pores to which it was hydraulically attracted and a 'disjoining pressure' that tended to separate the ice from the substrate. The pressure created by the suction force is affected by the crack geometry and the pressure of the ice and resisted by the tensile strength of the rock. Akagawa & Fukuda (1991) found that the pressure of water-ice in pore spaces in their experiment was up to 7 MPa, much greater than the tensile strength of the rock they were investigating. The ability of the water to move towards the freezing front is dictated, at least in part, by the permeability of a partially frozen zone on the warmer side of an ice-filled crack called the 'frozen fringe' (Figure 2.6).

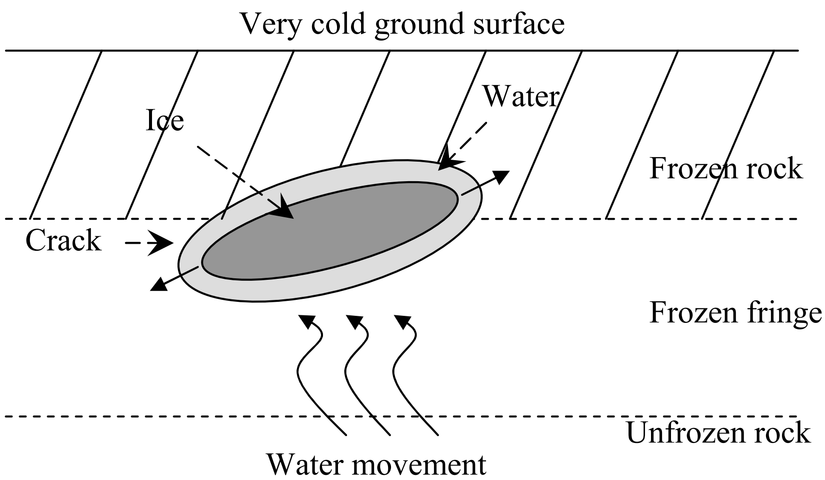


Figure 2.6: The freezing of a cracked rock, redrawn from Bland & Rolls (1998 p.90) and based on the work of Walder & Hallet, 1985

However, if crack growth was to be sustained it was necessary for high pressures to be maintained and so a continuous supply of water was required, although Akagawa & Fukuda (1991) demonstrated that the rock did not need to be saturated for ice segregation to occur. Numerical calculations indicated that for a Westerly granite frost weathering would be most effective in a temperature range of -4 ^{O}C to -15 ^{O}C (depending on crack length), and for a freezing rate of less than 0.1 – 0.5 ^{O}C hr^{-1} (Walder & Hallet, 1985). At temperatures above this range permeability is higher so that more water can pass through the frozen fringe but the maximum pressures reached are low and so unlikely to result in effective crack growth. At temperatures below -15 ^{O}C, permeability is so reduced that it can take years to reach maximum pressures and Hallet (1983) believed that the very low temperatures found in Antarctica would make this process ineffective there. In addition, if cooling rates are too rapid, permeability is quickly reduced and water does not have time to migrate. Selby (1993) noted that for low permeability rocks such as those under investigation in this research, prolonged freezing periods would be required.

2.6.3 Insolation Weathering

Insolation weathering includes weathering by thermal fatigue (due to repeated heating and cooling) and thermal shock (due to rapid heating or cooling) (Yatsu, 1988). Richter & Simmons (1974) found that heating rates of ≤ 2 ^{O}C min^{-1} did not result in permanent strain and it has subsequently been used as a threshold for thermal shock to occur. The low thermal conductivity of rock and the different thermal expansion behaviour of the constituent minerals are deemed to result in thermal fatigue. Solar radiation (or fire) can result in high temperatures at the rock surface but the poor thermal conductivity of rock means that a steep temperature gradient develops between the surface and subsurface resulting in stresses being established. These stresses may be of sufficient magnitude to cause fracturing or granular disintegration (Yatsu, 1988). Each rock mineral has different thermal expansion characteristics and stress sufficient to cause fracturing can be developed either within the mineral itself (i.e., where thermal expansion is different in different directions such as in quartz) or between minerals, particularly along grain boundaries. For instance, the thermal expansion of quartz is twice that of plagioclase or biotite (Ishimaru & Yoshikawa, 2000).

However, there has been considerable debate about whether these processes can produce the stresses necessary to crack rocks. For instance, Blackwelder (1933) noted that evidence at that time was slim and further investigation was needed to test the hypothesis of rock fracture by insolation. Similarly, Griggs (1936) found that a small block of granite did not respond to repeated heating and cooling tests after an equivalent of 244 years of simulated weathering. However, he did find almost immediate effects when the rock was cooled using a water spray rather than dry air, although the experimental procedures used by Griggs (1936) are open to criticism. For example, Warke & Smith (1998) have shown that the indirect method of simulating insolation used by Griggs (1936) should not be employed in laboratory simulations. The size of sample used can also influence the outcome (Goudie, 2000). Johnson et al. (1978 cited in Yatsu, 1988) found that a thermal threshold of 75 ^{O}C was required in granite to produce a differential stress of 10 MPa, sufficient to overcome the tensile strength of the rock.

2.6.4 Wetting and Drying

Repeated wetting and drying of rocks may also result in breakdown. This is based on the idea that a swelling pressure, caused by the addition of water to the adsorbed water in cracks or pores of rocks, may create a strain. As this additional water is removed during drying the attractive forces of the residual water molecules on either side of the crack pull it together again and these cycles of wetting and drying can result in repeated expansion and contraction of the crack or pore space. This in turn can produce cracking and flaking in the rock (Bland & Rolls, 1998).

One very specific wetting and drying mechanism is the ‘ordered water’ hypothesis (or hydration shattering). This theory was developed by Dunn & Hudec (1966) as an alternative to the volumetric expansion explanation for the break up of carbonate rocks in cold climates. They found that some ‘unsound’ rocks were susceptible to repeated wetting and drying. If the volumetric expansion theory was valid then there should have been more frozen water in these ‘unsound’ rocks but they found that less than 50% of water froze in these rocks compared to the sound ones.

At low temperatures water becomes ‘ordered’ i.e., individual molecules assume a particular orientation so that they carry a negative charge on the oxygen atom at one end and a positive charge on the hydrogen atoms at the opposite end. Clay platelets have an excessive number of +ve charges at their ends and an excessive number of –ve charges along their length. The water molecules can then become rigidly attached or adsorbed to the clay surfaces. In rocks with large pore spaces this has little effect but where pore spaces are < 5μm in diameter similar layers of rigid ordered water develop on opposite walls of the pore space and forces develop as the charges on the free ends (i.e., the –ve oxygen ions) repel each other. These forces increase with decreasing temperature (provided water remains unfrozen) and more layers are formed with increasing humidity (also a consequence of falling temperatures). However, if the pore spaces are too small then water cannot migrate, preventing the build up of stress. Fluctuations in temperature (and corresponding relative humidity) mean that water is being repeatedly adsorbed (or 'ordered'), with consequent stresses in the rock, and desorbed or disordered with subsequent relaxation of those stresses.

Experimental work by Hudec (1973) and Hudec & Sidar (1975) distinguished between sound rocks, which had more than 20% of their pore space available after saturation, and unsound rocks, which had less. A high percentage of pore space available after saturation meant that there was insufficient pressure to break up the rock. Unsound rocks were further differentiated between those that were 'frost sensitive' and those that were 'sorption sensitive' on the basis of the amount of freezable water (i.e., water that was absorbed rather than adsorbed) they contained (Table 2.4).

Table 2.4: Categorisation of sound and unsound Rocks

Rock Type	Pore space available after saturation	Amount of freezable water
Sound	High (> 20%)	High (> 40%)
Frost sensitive	Low (< 20%)	High (> 40%)
Sorption sensitive	Low (< 20%)	Low (< 40%)

If the amount of freezable water was high in rocks that had less than 20% of their pore space available after saturation then they were susceptible to frost weathering in the traditional volumetric expansion sense, otherwise they were sorption sensitive. Sorption sensitive rocks tended to saturate under high humidity conditions alone, for example fine grained sedimentary rocks. Frost sensitive rocks on the other hand were coarse grained and only saturated critically by the *absorption* of *bulk* water (Hudec, 1973). Hudec and Sitar (1975) also found that whilst the presence of clay was a common denominator in unsound carbonate rocks its presence even in substantial proportions did not necessarily mean the rock was unsound but that the clays had to be continuous and accessible to wetting.

Hudec (1973) found that there was an incremental increase in volume after each cycle of wetting and drying and so repeated wetting and drying fatigued the rock and the rock failed under tension. Hudec and Sitar (1975) measured the expansion and contraction of dry and saturated rock and found there was little difference for sound rocks but saturated sorption sensitive rocks expanded by a factor of 2 over dry rocks. Frost sensitive rocks experienced a small net expansion provided saturation was maintained. They found that for the majority of rocks frost action also contributed to the destruction of the rock.

White (1976) promoted the idea of hydration shattering still further by arguing that perhaps it was this mechanism rather than frost action that broke up bedrock in arctic and alpine environments. Fahey (1983) confirmed the complementary role of frost action in his experiments on schist and, although he found that frost action was more effective in producing breakdown of his aggregates he noted that the process of hydration operated throughout the year and was not dependent on crossings of the zero degree isotherm.

Hall & Hall (1996) undertook a series of experiments on sandstones and dolerites and argued that it was fluctuations in moisture alone that could cause rock breakdown and the presence of clay was not essential. However, the method of moisture application can affect the result so that those samples that were covered or half-covered in water had significantly greater mass loss (and of similar magnitude) than those that were simply sprayed. They stressed the synergies of this process with other processes such as frost weathering.

Bland & Rolls (1998) identified the factors that made rocks more vulnerable to wetting and drying as:

- The presence of clay minerals
- Structural weaknesses
- Low tensile strength
- Pore size and distribution

2.6.5 Salt Weathering

Fahey (1985), Selby (1993) and Goudie (1997) described the three recognised mechanisms involved in salt weathering: crystal growth, hydration and thermal expansion. The growth of crystals from solution may be due to several factors: decreased solubility with decreasing temperatures; evaporation of the solution or salt precipitation following the mixing of two different salt solutions (Goudie, 1997). The growth of large salt crystals occurs at the expense of smaller ones and they continue to grow until they completely fill the pores in a rock (Selby, 1993). Common salts have also been found to hydrate and dehydrate relatively easily in response to changes in temperature and humidity (Selby, 1993). For example, Sperling & Cooke (1980) found that magnesium sulphate expanded by 173% when hydrated and that thenardite tripled in volume when transformed to mirabilite. However, these expansion rates were dependent on threshold temperature ranges and relative humidity. For example, the threshold temperature for thenardite to transform to mirabilite is 32.4 ^{O}C. For temperatures less than this a critical (and high) relative humidity must be reached (Fahey, 1985). Cooke & Smalley (1968; cited in Selby, 1993) found that four out of five salts they tested had a thermal expansion greater than that of granite. For a common salt such as sodium chloride a rise of 54 ^{O}C gave a volumetric change of 1%, although the low thermal conductivity of rock probably limits this to the outer few centimetres (Selby, 1993).

2.7 RECENT COLD CLIMATE WEATHERING STUDIES

2.7.1 Until early 2000

Elliott (2003) reviewed the status of rock weathering research until early 2000 (Appendix 4). In particular she compared the research that had taken place in the Northern Hemisphere with that of Antarctica. She found that evidence from studies in the Northern Hemisphere that frost or salt weathering (either acting individually or together) were effective mechanisms in rock disintegration remained inconclusive. There also continued to be a lack of clarity on how these mechanisms work, with some studies noting that little debris is produced by the freezing and thawing of the rock (e.g., Lautridou & Seppala, 1986; Tharp, 1987). With a few notable exceptions (e.g., Lautridou & Seppala, 1986; Fahey & Lefebure, 1988), weathering studies were primarily undertaken in the laboratory and on sedimentary rock, usually limestones or sandstones. Although the importance of temperature, moisture and rock properties was recognised, there was no clear evidence as to which freeze-thaw cycle may be the most effective nor what type or concentration of salt. Little cognisance had been taken of insolation weathering in these Northern Hemisphere studies.

Research in the Antarctic on the other hand was conducted on a wide range of rocks, for example volcanics interbedded with conglomerates and sandstones (Hall, 1993a); quartz-micaschist (Hall, 1986 a, b, 1987), dolerite (Hall, 1993a) and tuff (Matsuoka et al., 1996). There were also field studies, either on the rocks themselves (e.g., Hall, 1997a, b; Matsuoka et al., 1996) or on rock blocks exposed to the local environment (e.g., Hall, 1986a, 1993a) or by visual inspection (e.g., French & Guglielmin, 1999). Frost weathering, if important at all, was determined to be highly localised. For example, Hall (1997a, b) found that in the Viking Valley on Alexander Island, Antarctic Peninsula (78^{O} 50'S, 68^{O} 21'W), whilst there were sufficient temperature oscillations to produce freeze-thaw, lack of moisture meant it only occurred in the more wet western and northern aspects. Similarly, Matsuoka et al. (1996) put the low rates of bedrock shattering within the Sør Rondane Mountains (72^{O}S, 22^{O}E) down to the low moisture content of the rock (30-40 % degree of saturation) rather than to any shortage of freeze-thaw cycles. However, on Livingston Island (62^{O} 40'S, 61^{O} 00'W), whilst the moisture was sufficient for frost weathering to occur, rock temperatures rarely fell below 0 ^{0}C and so again freeze-thaw was very localised (Hall, 1993a).

Other effects of micro-climate or micro-environment were also evident. For example, the insulation provided by snow could either prevent the thermal conditions necessary for freeze-thaw from occurring or slow down the cooling rate sufficiently to allow water migration and hence segregation ice and freeze-thaw to occur (Hall, 1993a). Chemical weathering was greatly enhanced by the presence of snowpatches (Hall, 1993b; Ishimaru & Yoshikawa, 2000). Even in arid areas, wetting and drying could also be present, (Hall 1997a, b) and salt weathering was deemed to play a major role in the Sør Rondane Mountains (Matsuoka et al., 1996) and the Dry Valleys (Johnston, 1972; Miotke, 1982b) but not in the Thiel Mountains (85^{O} 26'S, 86^{O} 46'W, Ishimaru & Yoshikawa, 2000).

The potential role of insolation weathering was stressed in several studies (e.g., Hall, 1998, 1999; Hall & Hall, 1991; French & Guglielmin, 1999) and in others cited as the predominant mechanism (e.g., Hall, 1997a, b; Ishimaru & Yoshikawa, 2000). The lack of mention of insolation weathering in the Northern Hemisphere literature was put down to other processes such as freeze-thaw or hydrolysis concealing it in the more temperate environments (Ishimaru & Yoshikawa, 2000). Hall (1997b) found that data collected at one minute intervals identified rates of temperature change in rock that were greater than that required for thermal shock to occur. Anderson (1998) using numerical modelling, found that for low albedo (<10%) granitic rocks and a high atmospheric transmissivity, frost cracking decreased monotonically with depth provided there was an ample supply of water.

The type of rock and its properties were also highlighted (Hall, 1986a; Matsuoka, 1995). For instance, the location and concentration of quartz within a quartz-micaschist affected not only its strength but also its moisture content and hence potential vulnerability to frost action (Hall, 1986a). He also found that moisture content varied over both time and space and even within the same rock type. Ishimaru & Yoshikawa (2000) observed that the rates of thermal expansion and the thermal conductivity for the quartz and plagioclase of the Nolan Pillar, a small granodiorite nunatak, were very different and hence encouraged insolation weathering.

Hall (1992) stressed that processes worked synergistically and used earlier work done on Signy Island (60^{O} 43'S, 45^{O} 48'W) to develop a series of flow charts detailing the different processes, their inter-relationships and the factors that controlled them. Each flow chart, for example freeze-thaw (or frost weathering p.109), included decision points, based on field and simulated data, to help identify the actual mechanisms involved. He concluded that an element that controlled one process (e.g. temperature change for freeze-thaw) could also exert an influence on others (e.g. thermal stress fatigue) and therefore the conditions that facilitated frost weathering weathering could also enable other processes such as wetting and drying, salt and/or thermal fatigue to occur.

Several studies identified some points of importance for laboratory experiments. For example, Hall (1986a) found that laboratory simulations sometimes exaggerated actual moisture contents and Matsuoka et al. (1996) suggested that the dominance of rock breakdown due to halite rather than thenardite in their field experiment was a result of the different temperature and humidity conditions used in the laboratory experiments.

Hall (1987) found that the strength of quartz-micaschist depended on both the location of the quartz inclusions and whether the load was applied parallel or normal to schistosity. He also noted that, even if the moisture levels used by Lautridou & Ozouf (1982) in their laboratory experiments were available on Signy Island, temperatures there rarely fell below –8 ^{0}C on other than a seasonal basis and hence the 500 cycles used in their experiments significantly exaggerated this real field situation.

2.7.2 2000 to 2005

Since early 2000 a number of papers have been published relating to both rock weathering in cold climates generally and Antarctica in particular and the most relevant to this research are reviewed here. Frost weathering continued to be the subject of some interest with both field and laboratory research having been conducted. Nicholson & Nicholson (2000) measured the response of ten different sedimentary rocks to temperature cycles of -18 ^{O}C to +18 ^{O}C. Samples were saturated at the outset and placed in distilled water to a depth of 30 mm throughout the experiment. They investigated both the percentage weight loss and fracture density but (with the exception of one outlier) found a very high correlation between the measures for these rock types. They also investigated the role of pre-existing flaws (as seen by the naked eye) in the deterioration of their rock samples. They identified four distinct modes of deterioration: rapid, severe disintegration; grain loss; fracturing and large scale fragmentation; scaling. They proposed four models to explain the modes of deterioration:

1. Rocks with high mechanical strength and low porosity: most deterioration occurred at pre-existing flaws

2. Rocks with low mechanical strength and high porosity: deterioration was associated with void dependent properties and micro-cracks rather than flaws

3. Moderately weak and moderately strong rocks: the influence of pre-existing flaws on deterioration was very variable

4. Rocks with strong textural properties (e.g. sandstone): deterioration was associated with granular loss

They concluded that pre-existing flaws were particularly important in the deterioration of stronger rocks but that their direct influence diminished in weaker rocks as the influence of other rock properties and environmental factors increased.

Nicholson (2001) undertook a series of laboratory tests (that did not attempt to replicate reality) on five different limestones and found that it was important to use a range of tests when comparing results across processes. For example, she found that the durability of the different rock types varied with the test (i.e., weight loss or fracture density) and/or the environmental conditions. She found that the freezing and thawing of the rock was more likely to result in detachment of rock fragments leading to weight loss whereas salt weathering was more likely to lead to incipient fracturing. Contrary to expectations she found that effective porosity (as measured using the displacement method) both increased and *decreased*. The freeze-thaw tests produced increases, decreases and no change in effective porosity depending on rock type but salt weathering always produced a decrease associated with weight gain and increased density, probably due to the retention of crystallised salts in pore spaces. She proposed that the decrease in effective porosity in the freeze-thaw tests could be due to throat blockage (by debris redistribution) or pores having been compacted in some way. The wetting and drying tests also produced an increase and a decrease in effective porosity, the former perhaps as a result of the break up of grain contacts and subsequent flushing out of loose debris. She proposed that an increase in total void volume in the samples could be the result of either increased pore connectivity by modification of existing pore structure and/or the generation of new voids

Lewkowicz (2001) investigated the near surface rock temperatures on a sandstone tor for more than a year, confirming the importance of using rock temperatures rather than air temperatures (except during the polar night) in weathering simulations. By applying a constant environmental lapse rate to the near surface temperatures he found that, although the timing and number of cycles through 0 ^{O}C were influenced by altitude, the relative importance of aspect was maintained regardless of elevation. He also found that the potential influence of snow blowing onto the rock surface was also independent of altitude.

Matsuoka (2001b) investigated the relationship between joint widening in sedimentary rocks in the Japanese Alps and the temperature and moisture conditions associated with them. An extensometer, consisting of two strain gauges, measured joint movement at a scale of thousandths of a millimetre. Although there were issues with the equipment as well as snow, four years of data were successfully collected at one site. After estimating the effects of thermal expansion and contraction of the extensometer and the bedrock Matsuoka found that longer term joint widening occurred at only one of the rock outcrops. Short term variations at this outcrop occurred during rapid freeze-thaw cycles particularly in autumn when crack temperatures decreased to – 1^{O}C. These generally resulted in small scale widening but once per year at the seasonal thawing period when near surface rock temperatures were at or slightly below 0 ^{O}C beneath a wetting snow cover, large joint widening (0.2 mm – 0.8 mm) occurred at the same outcrop. Widening progressed gradually for 1-2 weeks before reaching a maximum and then took 3-5 days to close once the crack temperature rose above 0 ^{O}C. Although, he was unable to determine precisely the origin of the joint widening (thermal stress versus frost weathering) or the critical factors that might produce it, he suggested that an additional source of moisture at the outcrop that experienced the overall crack widening might be the reason. He determined that the magnitude of joint widening was nearly proportional to frost depth and that short term freeze-thaw cycles and optimum moisture conditions could produce frost wedging to a depth of at least 20 cm. Most interestingly he found that frost wedging occurred even when the rock face was held at nearly constant temperature close to the freezing point and that generally, the temperature range at which wedging occurred varied with bedrock conditions, water availability and duration of freezing.

Murton et al. (2000, 2001) tested the premise of Walder and Hallet (1985, 1986) that ice segregation occurred in rocks just as it did in soils and that the segregated ice is most abundant at the top of the permafrost and bottom of the active layer (e.g., Mackay, 1972 cited in Murton et al., 2001). Their experiment on large (and small) blocks of chalk simulated, as closely as possible, the conditions likely to prevail in a cold environment under conditions of both perennial and seasonal freezing and thawing. They found that the unfrozen water content varied with position in the temperature cycle as well as with depth with the middle position in the active layer being generally the least moist. They found evidence of segregated ice and weathering at the base of the active layer as predicted, particularly in the block subjected to perennial freezing and thawing (i.e. underlain by a layer of permafrost). However, they did note the possibility that this was an artefact of the location of the sources of moisture in their experiment and that this needed further investigation.

The heave measured in the chalk block subjected to perennial freezing conditions was much greater than could be attributed to volumetric expansion alone and was attributed mainly to ice segregation but with a contribution from volumetric expansion. Sixty one percent of the heave occurred in winter and 39% in summer where the former was unidirectional (upwards). However, summer heave varied significantly in direction, amount and timing and was attributed to ice segregation. Ice lens growth occurred at approximately -0.2 ^{O}C to -1.8 ^{O}C, consistent with the theory of Walder and Hallet (1985, 1986) for this type of rock.

Davies et al. (2001) found that ice in discontinuities strengthened the joint when the ice was at low temperatures (e.g., -5 ^{O}C), making it stronger than ice free joints but weakened it as the ice warmed to 0 ^{O}C. Dixon et al. (2002) followed up the work by André (1995) in northern Norway on a biotite granite roche moutonnée. André (1995) had concluded that the most significant weathering processes were largely biological or biophysical. Dixon et al. (2002) used Scanning Electron Microscopy (SEM) and wavelength dispersive spectroscopy to examine samples taken from this site, which had an estimated exposure date of approximately 10,000 years; they assumed the rock surface was unweathered on exposure. They found evidence of mineral grain dissolution and a loss of chemical constituents as well as increased porosity near the surface indicating that chemical weathering had taken place but that there was little evidence of any substantial frost weathering. However, they also noted that the roche moutonnée was 75 % covered in lichen and that organic acids from these may also contribute to the chemical weathering.

Matsuoka (2001a) took an in depth look at the microgelivation of soft rocks compared to the macrogelivation of hard jointed rock as well as some of the issues of field versus laboratory studies. He identified two moisture parameters; the degree of saturation before freezing and the amount of water migration during freezing that governed frost weathering. In conditions of high rock saturation and a closed moisture system volume expansion and rapid (diurnal) freezing was favoured, whereas in low saturation, open moisture systems ice segregation and slow (seasonal) freezing prevailed. He concluded that field research on microgelivation should examine water accessibility, dominant freeze-thaw regime (diurnal, annual, interannual) and rock properties such as porosity and tensile strength. Investigations into macrogelivation of hard jointed rock should be performed in the field where a temperature change of only a few degrees can activate large scale breakup in the bedrock at a few metres depth. Rocks with a high internal surface area and low tensile strength favoured microgelivation whereas macrogelivation tended to take place in water filled joints.

Hall (2004) provided strong evidence for the freezing of moisture (the presence of exotherms, short lived increases in temperature of a few degrees resulting from the release of latent heat when ice forms) in his investigation into the thermal regimes at the surface and depth of paving bricks. However, he found that freezing occurred not only at different temperatures, including well below zero, but also at different times and depths so that on occasion the rock was frozen below the surface whilst thawed at the surface and vice-versa. Consequently it was difficult to predict a freeze-thaw threshold even within one aspect. He argued that high rock temperatures coupled with the presence of moisture meant that chemical weathering could take place, including in winter. He also found evidence that the threshold for thermal shock to occur had been crossed and concluded that rock weathering in cold regions could be a combination of chemical and more than one physical weathering process.

Ishikawa et al. (2004) monitored crack widths and rock temperatures in an andesite bedrock cliff in an alpine area of Japan. Cracks propagate when the stress intensity factor exceeds a threshold value that is dependent on the physical and chemical characteristics of the rock material at the crack tip. Crack propagation can be classified as either critical or sub-critical, depending on the rate of widening (Atkinson, 1982; 1984). Critical crack failure was attributed to a combination of high moisture (precipitation) input and/or sub zero rock temperatures whereas sub-critical crack growth was deemed to be a result of cyclic thermal stress at the crack tip. Rapid crack propagation was considered indicative of brittle failure whereas slow crack widening was probably the result of fatigue failure and/or stress corrosion (Ishikawa et al., 2004).

Sass (2004) investigated the distribution of moisture in a number of limestone rock outcrops using 2D resistivity and found that:

1. Freezing occurred between 0 ^{O}C and -1.0 ^{O}C

2. Moisture within the rock was distributed irregularly mainly because of the in-homogeneities of the rock itself

3. Pore water was usually frozen within 4-12 hours and the amount of water remaining unfrozen was directly related to the minimum temperature of the freezing event regardless of duration of frost

4. There was no evidence that this moisture moved to the freezing front regardless of length of freezing i.e., the amount of unfrozen water remained the same even during long periods of constant freezing, confirming the results of (Hall 1988b), but that it may be irregularly distributed

5. Pore water was pushed into the rock by expanding ice at the surface, with the push more likely to occur after a long frost free period in the presence of an external water supply; otherwise the water froze in position. The elevated values during the thrust appeared to be too high to be caused by the increasing water content alone and may be the result of the sudden movement causing temporary over saturation

He concluded that this thrust was most likely to occur in fractured rock with a low overall porosity and probably worked better when rain or melted snow had wetted the surface, resulting in 'frost-induced hydration weathering' (Hall, 1988c). He also found evidence of water movement towards the freezing front supporting the work of Walder and Hallet (1986).

In a subsequent paper, Sass (2005), reviewed several techniques to measure moisture in rock and reported on the outcome of investigations into moisture availability and its distribution in alpine limestone. He found that duration was more significant than the amount of water rainfall produced and that the inside of the rock was damper than the surface. However, below the outermost few decimetres equilibrium conditions existed between generally inward-directed capillary transport and outward-directed diffusion of water vapour. Moisture fluctuations in the outermost 1-2 cm of the rock were affected almost immediately by the prevailing weather conditions but at depths of 2-10 cm the water supply in the previous weeks or months became increasingly important for pore saturation. Long term moisture distribution was influenced by both insolation and precipitation but orientation to predominant direction of rainfall seemed of greater importance, perhaps countering or even exceeding the differences caused by radiation. He concluded that the likely favourable conditions for frost weathering to produce rockfall were in spring, summer and autumn, although it was unclear from the discussion whether he was talking about air or rock temperatures. He found that extensive rockfall occurred during summer periods of frost action and intense precipitation but that "due to the limited water supply, effective weathering is probably limited during the winter months" (p.372). He also concluded that shallow diurnal frost cycles would not produce effective weathering since they took place at a depth that was mostly dried out during the season in question. However, continuous frost could penetrate deeper and gain sufficient access to water so that frost shattering could occur. Consequently, he suggested that the importance of across zero cycles had been over estimated whilst the importance of moisture had been under estimated (Hall et al., 2002) and he agreed with Matsuoka (1991) that moisture content was a major control on frost shattering rate.

Elliott (2004, Appendix 4) measured the surface moisture characteristics of granite rocks in Victoria Land using sensors that recorded the presence or absence of liquid moisture on the surface of the rocks. She found that moisture (predominantly as a result of blowing snow) was present more often than might be supposed in that dry environment (up to 40% of the time). Consequently, processes that required the presence of moisture such as frost, hydration shattering or even chemical weathering could not be excluded as potential agents of rock breakdown in this environment as had sometimes been assumed (e.g., Campbell & Claridge, 1987).

The influence of salt on rock weathering was the subject of a small number of papers and although conducted in warm desert environments they are of interest here because of their discussion on the role of fog and the use of laboratory simulations. Migon & Goudie (2000) discussed the origins of the potassium rich granite landforms of the Central Namib that were of similar age to those studied in this research. They argued that it was not inherited weathering, as had previously been proposed, but rather present day conditions resulting from a combination of salt and advective fogs that were most influential in the coastal regions. They concluded that it was lithological and structural controls that produced the particular landforms so that tafoni for example, were restricted to the massive coarse Mesozoic granites.

Goudie et al. (2002) pointed out that laboratory simulations have two roles, as a predictor and, perhaps more usefully, as an aid to explanation. They established an experiment to examine in detail the relationship between rock breakdown (specifically chalk, although the chalk used was exotic to the simulated climates) and the availability of fog and moisture in a hyper-arid, hyper-saline weathering environment. They simulated 18 different weathering environments using six salt levels and three levels of fog application (0.5, 1.0 and 2.0 mm) applied weekly by a fine spray. They found that whilst there was no direct relationship between the levels of salt and the number of liberated pieces of chalk weighing more than 1 gram there was a relationship between the level of fog application and the number of liberated pieces, with the highest moisture level producing the greatest number. However, they also concluded that whilst fog might determine the rate of breakdown, salt might control the timing and rock type the style of response. The importance of recognizing that more than one weathering process may be operating (in this case wetting and drying in conjunction with salt weathering) was also raised, even where one process was deemed to dominate.

There has been a renewed interest in insolation weathering in recent years, in both warm and cold environments. For instance, Goudie & Viles (2000) exposed small oblong samples of marble to the kind of temperature regime they might experience in warm deserts. Rock strength, as measured by a sonic device, decreased rapidly during the first few temperature cycles and then tailed off. SEM analysis revealed that the calcite grains changed shape with temperature and grain boundary widening was observed, perhaps enabling other moisture dependent processes to operate. Viles (2005) undertook a 3 year study of the weathering of granite and marble blocks in the Central Namib Desert. She found little evidence of thermal shock events at one site, except in the presence of moisture, but suggested that thermal fatigue may be an important process there.

However, French & Guglielmin (2000) concluded, on the basis of the low (air) temperature range measured inside a tafone together with lack of evidence from thin section analysis of grains being forced apart, that it was not thermal stress but rather saline moderated freeze-thaw cycles and the physical properties of quartz at low temperatures that produced the weathering. Thin section analysis of samples from some of the tafoni in the vicinity of the Italian Antarctic Research station at Terra Nova Bay had revealed that there was high fracturing of the quartz crystals compared to the feldspar or biotite crystals and that the cracks in the quartz stopped at contact with the feldspar. However, they also acknowledged that their lack of detailed field data on rock humidity, rate of ground freezing and speed and amplitude of rock temperature changes must make this a tentative conclusion.

French & Guglielmin (2002a, b) investigated cryogenic grooves and rock varnish on a small granite nunatak in northern Victoria Land. Although the precise formative mechanism was unclear they concluded that the grooves were a result of mechanical weathering where rock fragments produced by the preferential disintegration of quartz grains at sub-zero ground temperatures were removed by short lived episodes of meltwater activity. They discounted frost weathering on the basis of the low mean annual air temperature, but acknowledged later that rock temperatures fluctuated quite widely and they suggested that the increasing brittleness of quartz with low temperatures might be important as well as thermal shock and/or stress fatigue acting on the different minerals in the rock. They were unable to account for the lack of similar grooves in the Arctic except possibly for a difference in latitude, although their existence in the humid tropics is clear (French & Guglielmin, 2002a).

Hall & André (2001) advocated the use of high frequency (1 minute interval) rock temperature data to investigate the potential for thermal stress weathering to occur in Antarctica, particularly as the aridity of the area may preclude frost weathering from taking place. They found evidence that the 2 ^{O}C min^{-1} threshold for thermal shock to occur had been crossed, although not on all aspects, and that rock fracture patterns were similar to those found in laboratory tests into thermal shock. They pointed out that not only was this threshold independent of temperature (i.e., it can occur anywhere in the temperature scale) but that it did not require the presence of water. In a summary of the work of Marovelli et al. (1966), Hall & André (2001) stated that thermal failure was a result of a combination of rock properties, tensile strength and the magnitude and duration of the stress generated by the thermal change.

In a subsequent paper, (Hall & André, 2003) recommended the use of even higher frequency measurements (20 s intervals) together with micro-thermocouples ($\leq$ 0.15 mm diameter). Using this instrumentation on the surface of a sandstone tafone they found that, depending on cloud and snow conditions, there were frequent short term crossings of the 2 ^{O}C min^{-1} threshold for thermal shock, regardless of aspect. In addition, it was possible for more than one aspect to experience this magnitude of temperature gradient at the same time and that large thermal changes in more than one direction could take place. In contrast, they found no evidence of water freezing within the rock and concluded that, at least in this dry region of Antarctica, thermal stress might be more significant than frost in producing rock breakdown. However, they also cautioned that care was needed when interpreting these high resolution measurements.

Zhu et al. (2003) investigated the unidirectional impact of thermal insolation on cubes of four different rocks (gneiss, diorite, and two types of granite) from the Kunlun Pass area of the Tibetan Plateau. The cubes were initially exposed to an ambient air temperature of -8 ^{O}C and then to simulated solar radiation in a low temperature cabinet. Surface and subsurface rock temperatures were measured on one set of samples that had been saturated in pure water and one set that had been saturated in a 10% sodium sulphate solution. They found that once the simulated insolation had been removed the rate of temperature decrease of samples saturated by water was faster than that of the samples saturated by a salt solution. In addition, the rate of decrease was generally greater than the critical value of 0.1 ^{O}C min^{-1} found by Battle (1960) for water saturated rock breakdown. Evidence of a temperature rebound consistent with rocks being saturated to -4 ^{O}C was found much more frequently in the water saturated samples than in those saturated in a salt solution, supporting the hypothesis that salt inhibits frost weathering (Cooke, 1979; McGreevy & Whalley, 1985). They also found evidence that the mineralogy of the samples influenced the simulated thermal regime so that the sample with a higher proportion of black minerals had a higher temperature during times of insolation. In addition, the ultrasonic wave transmitting rate decreased for all samples saturated by water but increased for all those saturated in the salt solution.

Guglielmin et al. (2005) undertook an extensive and detailed multi-disciplinary study of granitic weathering forms at three locations in northern Victoria Land. They found very little evidence of thermal shock events at a depth of 5 mm in a granite tor, although concluded that it could play a role in weathering of the outermost layer of rock that is fully exposed to solar radiation. Their temperature measurements in the tafoni did not enable them to rule out thermal stress associated with the differential dilatation coefficients of the various minerals as a mechanism. The number of *potential* freeze-thaw events defined as either crossing of 0 ^{O}C or – 1.6 ^{O}C as previously calculated (Prick et al., 2003) varied from year to year but there was little difference between aspects. Included in their investigation was an analysis of the effects of vegetation on weathering and they found that at least some of the processes acting on the tafoni were the result of mechanical weathering by lichen as well as by salt formation and/or hydration.

André & Hall (2005) studied ten alveolized sandstone boulders on Alexandra Island, Antarctic Peninsula, and described evidence of both mechanical biological processes and salt efflorescence. They distinguished between the processes of tafone initiation, which they attributed to salt weathering, and present day weathering activity, which they concluded was largely the result of thermal weathering. However, they also found potential evidence in places of salt and frost weathering acting together, and attributed the overall weathering effects in this environment to a suite of processes.

The need to recognise the complexity of the rock weathering system and the inter-relatedness of the processes continued to be stressed (Goudie, 2000; Warke, 2001; Whalley & Turkington, 2001). Warke (2001) discussed the complexity of weathering dynamics in the natural environment where the action of one weathering process may enhance the efficacy of another to produce much greater deterioration than would otherwise be expected. In addition, she noted the potential for models to help disentangle the temporal and spatial variability of weathering processes. Whalley & Turkington (2001 p.1) continued this theme and, after reminding researchers of the integral role that weathering has in geomorphology, recommended the use of a systems approach to weathering. They argued against the division of weathering into physical, chemical etc., as weathering processes do not operate in isolation but as an 'integrated suite of physico-chemical and biological processes'.

Whalley & Turkington (2001) also raised the issue, and difficulties, of linking small scale processes to large scale landscape change. Viles (2000) had earlier noted the need to get a clearer understanding of the linkages between small-scale weathering processes and long-term landscape evolution as well as the need to integrate a variety of techniques to get a deeper understanding of the rate and nature of weathering of a bare rock surface. In a subsequent paper, Viles (2001 p.63-64) identified four major scale issues in the recent weathering literature:

1. Are there characteristic spatio-temporal scales of landforms and processes?

2. Whether scales of process observation are the same as the scale of process operation. For example, weathering rates based on 1-2 years being extrapolated to explain landform development over hundreds or thousands of years or laboratory rates to field situations.

3. How to upscale observations made at the microscope scale to the weathering landform scale and the linked problem of downscaling.

4. How do different scales of processes and events interact to produce the geomorphology we see around us?

A number of papers have raised the importance of ensuring that laboratory experiments and simulations in particular should reflect real world conditions as closely as possible (e.g. Warke, 2001). Goudie (2000), after giving a brief but comprehensive history of experimental physical weathering recommended that the temperature cycles employed in simulations should be based on those measured in the field with modern dataloggers. He also reviewed and highlighted inadequacies in the previous methodology and design of some experimental studies, emphasising that careful attention was needed around sample shape, texture, dimensions and rock properties as well as the importance of sufficient replicates. He also discussed at some length the need to balance time constraints on the researcher against real world conditions in determining the number of cycles to be employed. Viles (2005) presented an extensive set of rock temperature and moisture data that demonstrated the complexity of rock temperature cycling and the oversimplification likely to be used in laboratory simulations.

Warke (2000) investigated the relationship between rock weathering processes at the rock/air interface and the micro-climate. She argued that one of the reasons for disparity of results between laboratory and field studies may be due to the persistence of the idea that macro/meso-scale climatic parameters are an accurate representation of micro-scale conditions and as such are used in both laboratory experimental design and in the interpretation of field based observations. She discussed ways to improve the integration of field and laboratory studies including using micro-data to inform laboratory design.

In summary, investigations into the role of frost weathering have constituted the majority of papers. Although these have been conducted mostly in the Northern

Hemisphere they have included both field (e.g., Matsuoka 2001a) and laboratory (e.g., Murton et al., 2000, 2001; Nicholson, 2001) research. Laboratory experiments again focused on sedimentary rocks (Murton et al., 2000, 2001; Nicolson & Nicholson, 2000; Nicholson, 2001) and saturated conditions (Nicholson & Nicholson, 2000; Nicholson, 2001) whereas field experiments focused on a range of rock types (Hall, 2004; Ishikawa et al., 2004; Matsuoka, 2001a) and environments (e.g., Hall, 2004; Ishikawa et al., 2004). Particular attention was given to the presence and/or role of segregation ice against that of volumetric expansion in three studies and these concluded that both processes could operate, depending on the particular conditions: high saturation, closed moisture systems and rapid freezing favouring volumetric expansion with low saturation, open moisture systems and slow rates of freezing favouring ice segregation (Matsuoka, 2001b; Murton et al., 2000, 2001). Sass (2004) clearly demonstrated the presence of segregated ice in his 2D resistivity field experiments.

Nicholson (2001) found that her sedimentary rocks responded differently to different weathering processes: weight loss for frost weathering, incipient fracturing for salt weathering and a variety of internal changes for repeated wetting and drying. Ishikawa et al. (2004) found that andesite cracked critically due to the freezing of water in the crack tip but subcritical crack growth was more likely a response to cyclic thermal stress. The temperature at which rocks froze was found to vary and could be close to the freezing point (Matsuoka, 2001a) or well below it (Hall, 2004).

The role of moisture was either the primary focus of a number of papers (Elliott, 2004; Sass, 2004, 2005), investigated as part of the research (Lewkowicz, 2001) or was found to contribute to the weathering response of the rock (Matsuoka, 2001a). Elliott (2004) and Lewkowicz (2001) both noted the presence of blowing snow in their studies and recognised the role that this might play in determining weathering processes (Elliott, 2004). Sass (2004, 2005) provided field evidence of the distribution of water in rock and critically reviewed a number of different methods of examining this. Most importantly he found that it was not the quantity of precipitation that was significant but the duration that the rock surface was wetted (Sass, 2005). He noted that the predominant direction of rainfall appeared to be more important than insolation in maintaining moisture distribution in the rock, similar to the conclusion of Lewkowicz (2001) that the influence of blowing snow was independent of altitude.

Investigations into salt weathering were conducted either in warm deserts or in the laboratory under warm desert conditions but again stressed the important influence of moisture and its availability in the guise of fog (Migon & Goudie, 2000). Goudie & Viles (2000) explored the effect of insolation weathering on samples of marble under warm desert conditions. Research into thermal or insolation weathering was almost as popular as frost weathering, although the conclusions were not definitive. For instance, French & Guglielmin (2000) determined that it was not an important process in their study of tafoni but might be responsible for the cryogenic grooves found on a small granite nunatak (French & Guglielmin, 2002a). However, Hall & André (2001, 2003) were the main proponents of the potential of insolation weathering in rock breakdown in cold environments. They proposed that conditions conducive to thermal shock and thermal stress did occur if the instrumentation used to measure rock temperatures was sufficiently sensitive.

Salt weathering, together with other mechanisms, was noted in a number of papers (Goudie et al., 2002, Zhu et al., 2003) and the idea that more than one process may operate has continued to be stressed. For example, Guglielmin et al. (2005) concluded that mechanical weathering by lichen as well as by salt formation and/or hydration could account for weathering of a granite tor in northern Victoria Land. André & Hall (2005) also raised the potential for salt and frost weathering to act together in their examination of weathering in sandstone boulders on Alexander Island. However, Zhu et al. (2003) found evidence to support the hypothesis that salt inhibited frost weathering in their investigations of several rock types from the Tibetan Plateau. The artificial division of rock weathering into physical, chemical, biological was stressed by Whalley & Turkington (2001) and the issue of translating small scale rock weathering studies to large scale landform evolution raised. Viles (2001) also highlighted this problem and summarised the scale issues involved in weathering studies. Some studies noted that biological or chemical processes might operate in Antarctica (Dixon et al., 2002; Elliott, 2004; Guglielmin et al., 2005; Hall, 2004).

The comparison between laboratory and field studies has continued to be raised with recent papers stressing the importance of replicating field conditions as closely as possible in any laboratory experiment (Goudie, 2000; Warke, 2001) and Lewkowicz (2001) again confirmed the need to use rock rather than air temperatures in these experiments. Some of the pitfalls of not using real world conditions were described

(Goudie, 2000) and ways of mitigating some of these discussed (Warke, 2001). However, some studies continued to use unrealistic moisture and temperature conditions (Nicholson & Nicholson, 2000; Nicholson, 2001; Zhu et al., 2003).

Antarctic research was conducted either on the Antarctic Peninsula (André & Hall, 2005; Hall & André, 2001, 2003) or in northern Victoria Land, particularly in the vicinity of the Italian base at Terra Nova Bay (Elliott, 2004; French & Guglielmin, 2000, 2002a, b; Guglielmin et al., 2005). These studies generally recognised that one or more weathering processes might operate (e.g. Elliott, 2004; André & Hall, 2005; Guglielmin et al., 2005). In particular, they supported the potential for thermal stress and/or thermal shock to be either the predominant mechanism (French & Guglielmin, 2002a; Hall & André, 2001, 2003) or at least to contribute to rock breakdown in these environments (André & Hall, 2005; Guglielmin et al., 2005).

2.8 SUMMARY AND RELEVANCE FOR THIS RESEARCH

Rock weathering is an important but highly complex process. In the context of this research it is its role in providing materials and nutrients for soil development that is most relevant. Its complexity is a result of the wide range of factors involved so that Ollier (1984 p2) stated that:

> *'At first sight weathering seems a hopelessly complicated subject, with a multitude of processes operating on an endless range of rocks and minerals under a great variety of climate and hydrological conditions'*

Factors include climate (especially the rock micro-climate), the properties of the rock and time (Robinson & Williams, 1994) and these can operate individually or synergistically (Goudie, 2000; Warke, 2001; Hall, 1992). In addition, rock weathering is a relatively new research field for geomorphologists, who have only really given it focus since the middle of the 20th century according to Yatsu (1988) and Nordberg and Turkington (2004).

The combination of complexity and relative youth of the research area for geomorphologists has meant that whilst a number of potential rock weathering processes have been identified, there is as yet no consensus on which may operate in cold climates nor on the mechanisms or driving forces behind them. For example, there is ongoing debate about whether it is frost weathering or insolation weathering that is the most active in these environments (Hall et al., 2002). Although arguments abound about the validity of insolation weathering, Hall and André (2001, 2003), concluded that this mechanism could be valid in certain circumstances. It was also acknowledged that more than one process may operate at the same time and that these could be complementary, for example frost weathering and hydration shattering (Fahey, 1983).

Nor is there agreement about whether it is volumetric expansion or ice segregation that is the driving mechanism for frost weathering. McGreevy (1981), summarised the field data to that date which contradicted the conditions required for the volumetric expansion of water to occur, whereas Matsuoka (1990a) demonstrated that both the volumetric expansion theory and the adsorption theory were valid, but that their importance differed for different rock types. More recently it has been recognised that local environment conditions and/or rock type may mean that a range of different processes and/or mechanisms may be valid (e.g. Warke, 2000).

Sass (2005) re-affirmed that the availability of moisture and freezing rates were important to frost weathering as well as to other processes. He also found that it was the length of time that the rock was wet, rather than the quantity of precipitation that was critical. Nicholson & Nicholson (2000) highlighted the role of pre-existing flaws in producing rock breakdown. Nicholson (2001) found that different processes produced different types of response in the rock. For instance, frost weathering produced weight loss whereas salt weathering resulted in incipient fracture.

The primary focus for this study was on the response of small intact rock samples to simulated conditions in a laboratory and the ability of a rock to resist breakdown is a function of its strength. For an isotropic rock such as granite, the more porous it is and the larger and more angular its grains the lower its compressive strength. In addition, tensile strength decreases with increasing quartz content and is affected by the presence of micro-cracks and their geometry. Fatigue failure in the hard rocks under consideration here is likely to be a result of micro-crack extension. Therefore, when considering the strength of granitic rocks a comparison of porosity, grain size and shape as well as quartz content and the presence of micro-cracks is important and these were all investigated in this study (Chapter 3 & 4). Other factors may affect rock strength, for example confining pressure or shear strength, but this research was interested in what was happening at or near the surface of exposed rock and so confining pressure and changes in it were not considered to be relevant. It was the ability of the rock to withstand granular disintegration or flaking and/or small scale surface wedging or near surface crack propagation that was of interest. The scale of investigation (Viles, 2001), and the use of micro-climate data when replicating field conditions in the laboratory (Warke, 2001), have also been raised.

In summary then, whilst there is no agreement on which processes may be the most dominant in particular cold environments there does appear to be agreement that:

- It is the micro-climate of the rock that is important, not the atmosphere i.e. it is the temperature and moisture conditions of the rock itself that determine weathering rates

- The properties of the rock such as grain size, quartz content and porosity are fundamental in determining the response of the rock to the differing processes

- A range of processes can operate in different environments depending on the availability of moisture and the temperature conditions

- The particular mechanism driving individual processes may also depend on the particular temperature and moisture regime so that frost weathering for example can be the result of either volumetric expansion or ice segregation depending on circumstances

- Laboratory experiments need to replicate as closely as possible the rock environment rather than that of the atmosphere

The complexity of rock weathering involving a range of critical factors, processes and outputs is best described by a process-response system (Figure 2.7). This highlights the range of factors involved, both climatic and related to the rock itself as well as the different ways that rock might respond to the processes. Climate needs to be considered at both the macro- and micro-scales, where the latter is taken to include the moisture and temperature conditions at the grain surface.

The properties of the rocks include those that are related to moisture such as porosity, as well as temperature, for instance thermal conductivity. A variety of processes can operate and may aid or inhibit each other. The subsequent changes in the rock can be distinguished between those that are external such as flaking or granular disintegration or internal including changes in void space or mineralogy. Fracturing can be either internal (micro-cracking) or external.

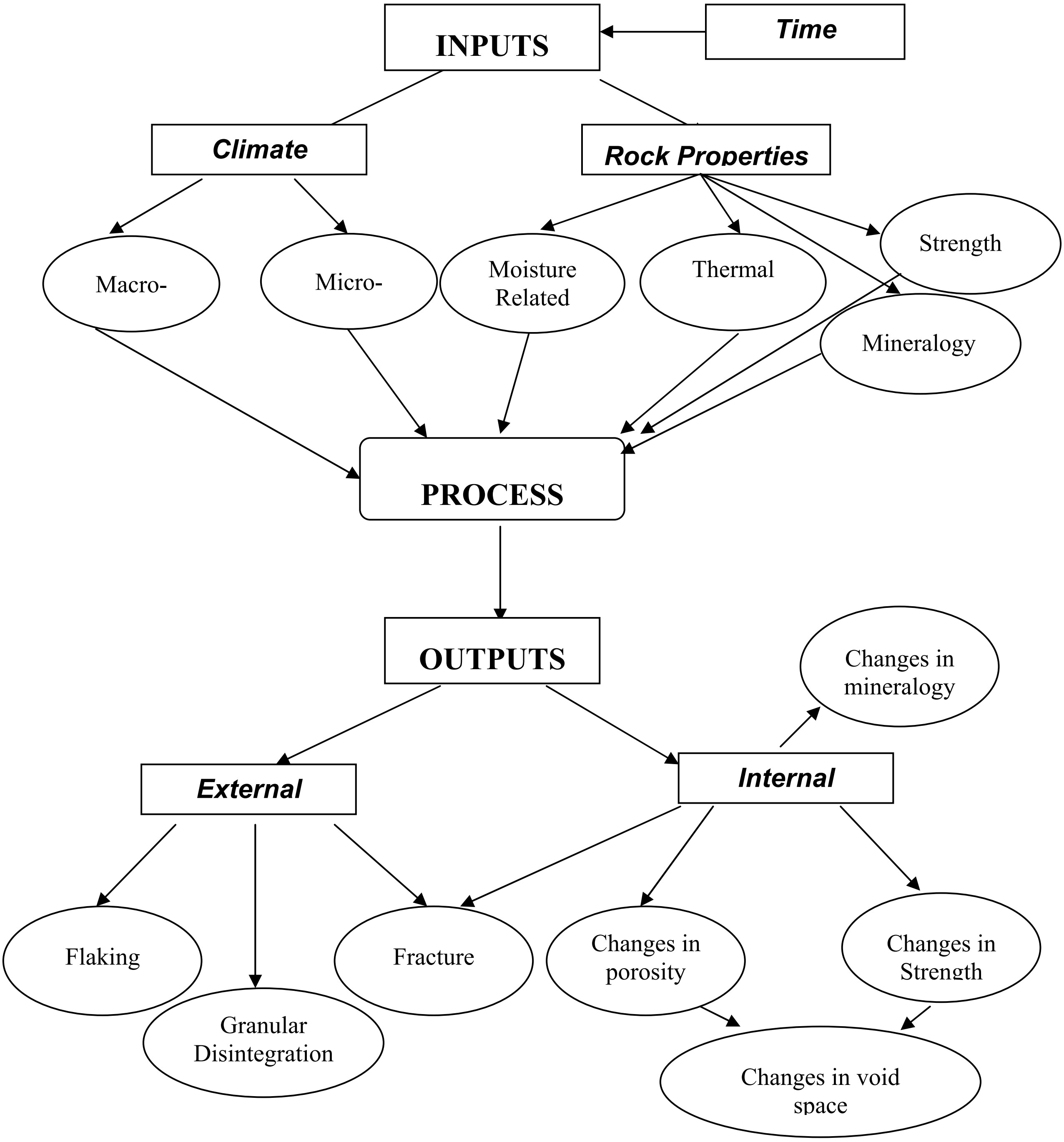


Figure 2.7: Relationship between inputs, process and outputs in rock weathering studies

Table 2.5 summarises the different processes and proposed mechanisms and the conditions under which they are deemed to operate. Discussion of the likelihood of their operation in the environments encountered as part of this research is included in the summary of Chapter 3.

Table 2.5: Summary of the different physical weathering processes and mechanisms and the requirements for their operation

Process and/or Mechanism	Requirements
Freeze/Thaw	
Hydraulic pressure hypothesis	High degree of surface saturation Rapid surface freezing
Crystallisation pressure of ice	Permeable rock Ongoing supply of moisture
Volumetric expansion	High degree of saturation Rapid rates of freezing Crossing of 0 ^{O}C Closed system Long, thin cracks
Capillary/adsorption theory	Slow rates of freezing Porous rock T≤ -5 ^{O}C Permeable rock Open system of moisture & ? high saturation Unidirectional freezing Cracks large compared to grain size
Insolation Weathering	
Thermal shock	Heating rate > 2 ^{O}C min^{-1}
Thermal stress fatigue	Repeated heating and cooling but range and frequency unknown
Wetting and drying	
Wetting & drying	Humidity fluctuations
Ordered water hypothesis	Humidity fluctuations Presence of clay
Salt Weathering	
Crystallization from solution Hydration Thermal expansion	Presence of salt Decreasing temperatures to decrease solubility Temperature and humidity fluctuations

There are a number of approaches to estimating weathering intensity and rate in both the field and laboratory and these are discussed further in Chapters 3, 4 & 6. At a more conceptual level and by building on the work of Pope et al. (1995) and Trudgill (2000), the overall rate of physical weathering (i.e. as a result of all processes acting in combination) can be expressed as:

$$dW/dt = f\{W_f, W_i, W_h, W_s\} \quad (1)$$

where W = amount of weathering; t = time and W_f is weathering due to frost action; W_i weathering due to insolation; W_h weathering due to wetting & drying and W_s salt weathering.

CHAPTER 3

FIELD SITES AND MEASUREMENTS

3.1 INTRODUCTION

The primary purpose of the fieldwork was to provide the data needed to undertake the laboratory simulations. A summary of the data collected and the frequency of collection are given in Section 3.2 and Section 3.3 describes the field sites and locations. Rock surface and subsurface temperatures (Section 3.4) and moisture levels (Sections 3.5 & 3.6) in particular were measured. Local climate data were gathered during times of actual field visits and were recorded to coincide with the subsurface rock moisture measurements. The data included air temperature, relative humidity, wind speed and direction as well as type and extent of cloud cover. In addition, automatic weather station (AWS) data from the nearest installations were obtained (Section 3.7). The characteristics of the rock such as albedo, grain size and hardness were also determined but these are discussed in Chapter 4 along with the results of a variety of laboratory tests.

3.2 DATA COLLECTION

Every effort was made to collect data over as long a timeframe as possible and ideally, for more than one season. However, this was constrained by practical considerations including the ability of Antarctica New Zealand to provide access to the sites. Table 3.1 gives the dates for which continuous data were collected, the frequency of collection and the aspect to which it relates. Logistics meant that only two sites could be visited in the 2002/03 season and two in the 2003/04 season but all four locations were visited in the final 2004/05 season. Most sites were visited twice in each season, at the beginning to undertake initial measurements and to set up the equipment to record the required data and at the end to download the data and dismantle the equipment. However, Teall Island was visited only once at the beginning of the 2003/04 season and once at the beginning of the 2004/05 season.

Table 3.1: Times, aspect and frequency of data collected in the field

Location	Dates of Continuous Data Collection			Frequency of Collection	Aspect for which collected
	2002/03	2003/04	2004/05		
Gneiss Point	25/10/02 – 18/1/03	N/A	N/A[1]	1 hour	S, W
Victoria Valley	30/10/02 – 25/1/03	N/A	N/A[1]	1 hour	N, H[2]
Terra Nova Bay	N/A	14/11/03 – 14/1/04	17/1/04 – 31/10/04	1 hour 2003/04 3 hour 2004/05	S, W W
Teall Island	N/A	20/11/03 -	18/11/04	3 hour	S, W

[1] Excludes one minute data which was collected during every visit
[2] Horizontal

The frequency of data collection varied depending on circumstances and timing of visits. In order to investigate the potential for thermal shock to occur, one minute surface and subsurface temperatures were collected during each and every visit for a minimum period of 48 hours (not shown in Table 3.1). For those locations where two visits were able to be made in the same season hourly averages were collected. However, three hourly averages were used when over-winter measurements were undertaken to ensure minimal drainage on the datalogger power supply as well as memory storage (Table 3.1). It was also assumed that winter fluctuations would not be as frequent or as great as in the summer and so minimal loss of information would occur, although this did not turn out to be the case and there was considerable variation in rock surface temperatures even during the winter (Section 3.4.2).

The surface and subsurface rock temperatures were measured using thermocouples and these, together with the sensors used to determine surface moisture, a pyranometer which recorded solar radiation and a thermistor required to provide the reference temperature for the thermocouples, were connected to a Campbell Scientific CR10X datalogger (Appendix 1). This particular logger was chosen as it has a non-volatile memory and is able to store 62,280 data items. Two new loggers that had been specifically tested to work down to temperatures of -40 ^{O}C, were used for the 12 month measurements at Teall Island. However, an untested one was used for the over winter measurements at Terra Nova Bay. Nevertheless, it continued to operate over the winter months. Battery life was supplemented by solar panels and, at Teall Island, by a wind generator (Figure 3.1). The latter was destroyed at some point during the winter of 2004 but the combination of this, additional batteries and the solar panels ensured that data were collected for the full period. The execution interval on the logger was set at 10s (Appendix 2).

Figure 3.1: Wind generator established to supply additional power to the datalogger over the winter period

3.3 LOCATIONS AND DESCRIPTIONS

In keeping with the requirements of the Latitudinal Gradient Project, field locations were chosen to provide as great a latitudinal perspective as possible but exact locations were selected on the basis of accessibility and rock group. A single rock group, Granite Harbour Intrusives, had been identified in order to minimise the influence of different rock characteristics on the laboratory simulations and within this rock group outcrops of medium-coarse grained granite were targeted. Three locations provided a latitudinal variation of approximately 4.5 degrees: Terra Nova Bay (74^{O} 41'S, 164^{O} 07'E); Gneiss Point (77^{O} 24'S, 163^{O} 42'E) and Teall Island (79^{O} 03'S, 161^{O} 56'E). A fourth, Victoria Valley (77^{O} 23'S, 161^{O} 55'E), provided a coastal/inland perspective. Figure 3.2 shows the location of the research area in relation to Antarctica as a whole and Figure 3.3 is a satellite image of the Victoria Land Coast with the four research sites and nearest Automatic Weather Stations marked.

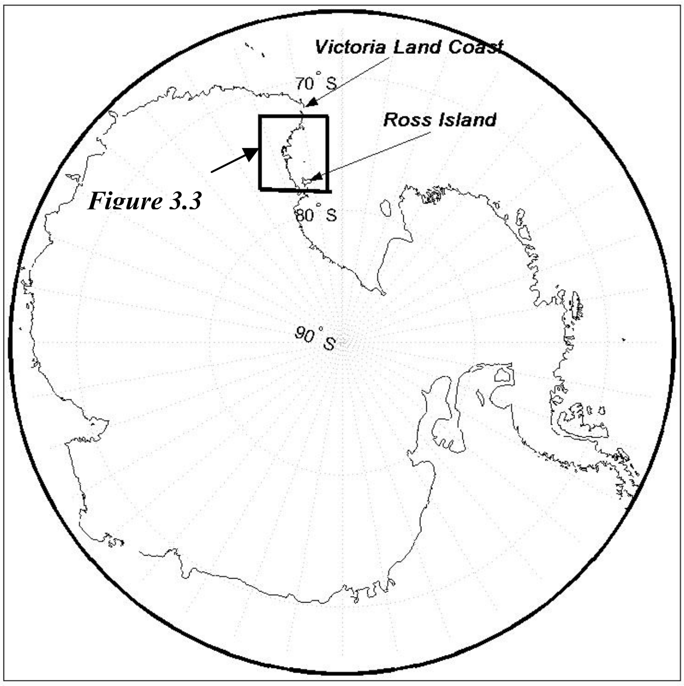


Figure 3.2: General location of field sites in relation to the Antarctic Continent

Two aspects were investigated at each location: south and west were chosen for the coastal sites as it was anticipated that these would give the greatest contrasts in terms of climatic conditions. Carrying out measurements on all four aspects would have been ideal but equipment constraints, combined with difficulties finding sites that allowed 360^{O} access, meant this was not possible. Descriptions of each of the four sites are provided in order of visit in the sections that follow.

3.3.1 Gneiss Point

Gneiss Point (77^{O} 24' S, 163^{O} 42' E) is located within a few hundred metres of the coast close to the Marble Point airstrip and directly west from Ross Island (Figures 3.3 & 3.4). The sea ice melts for brief periods most summers. The Point is a relatively flat plateau approximately 50 metres above sea-level and is dissected by a number of small ephemeral streams running in an approximately north-south direction. A landing strip for helicopters and an automatic weather station are nearby (Figure 3.4). The area is characterised by medium to large boulders and rock outcrops (Figure 3.5). At the time of the first visit in October 2002 the site was covered in snow to a depth of about 15 cm.

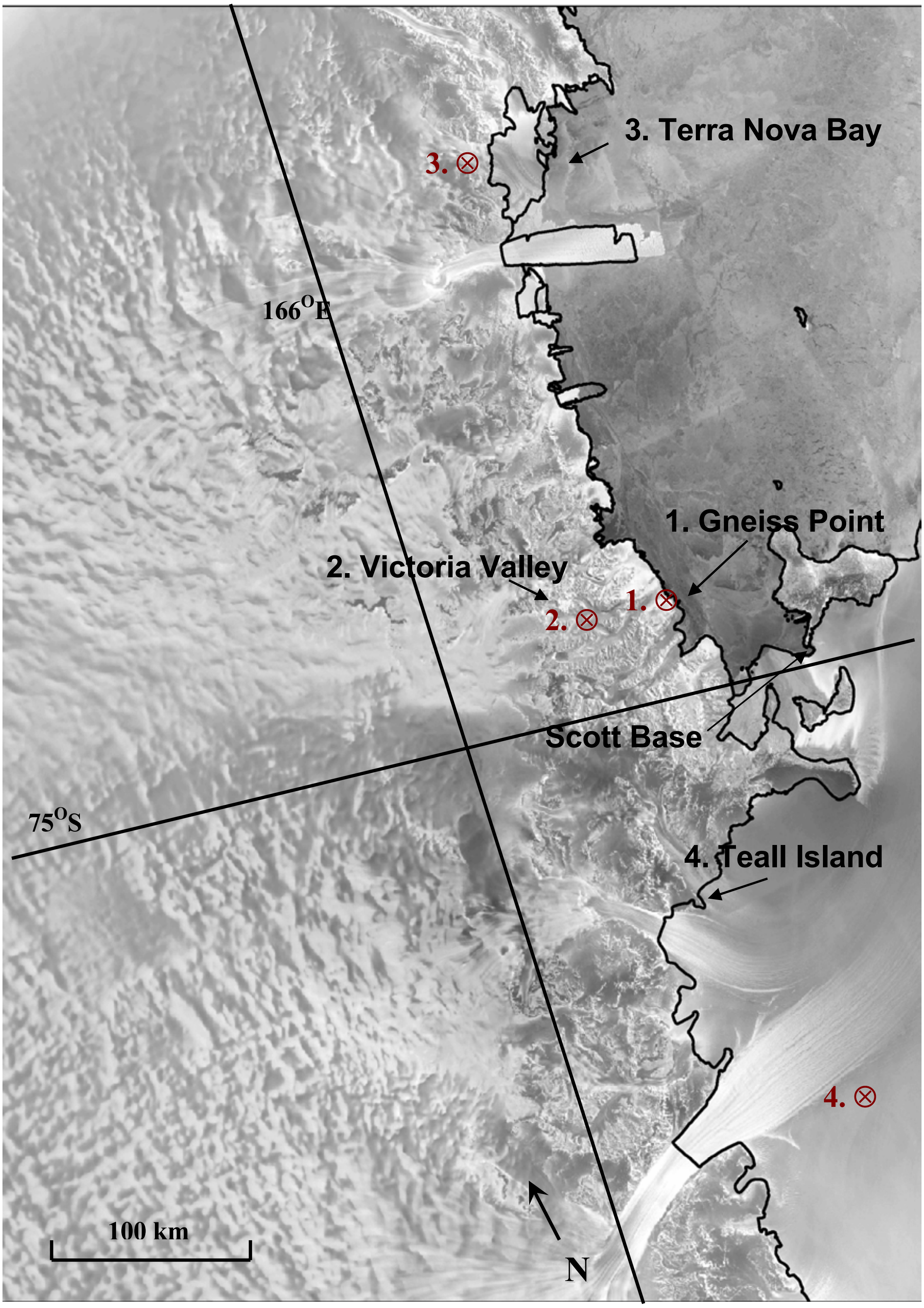


Figure 3.3: Satellite image of the Victoria Land Coast showing the four field locations in order of description and the nearest automatic weather stations (numbered circles), 1. Marble Point. 2. Lake Vida. 3. Eneide. 4. Marilyn. The location of Scott Base is also indicated. Base image courtesy of Paul Barr, Gateway Antarctica

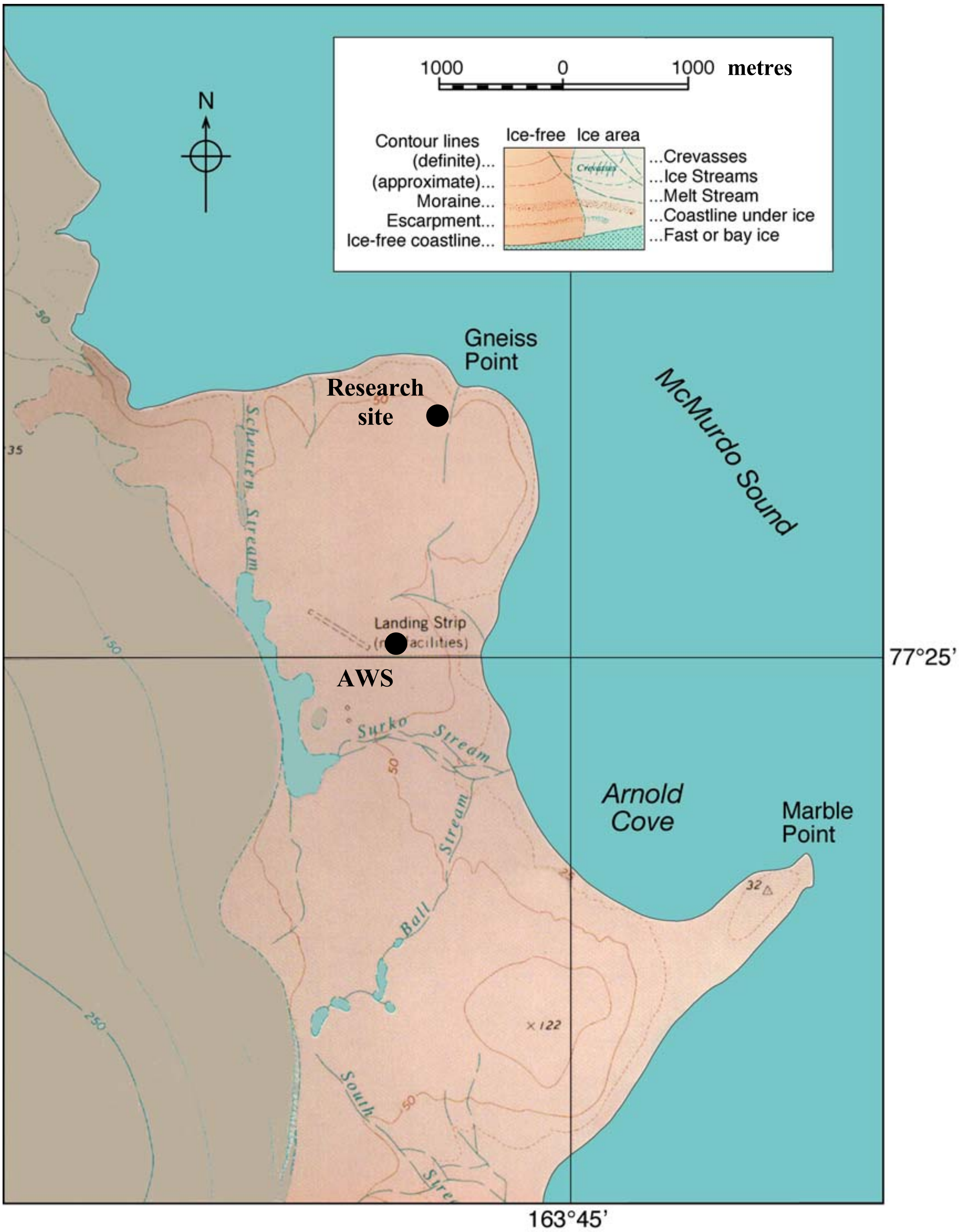


Figure 3.4: Location of research site, automatic weather station and ephemeral streams at Gneiss Point. Source: USGS 1: 50 000 Topographic Series, Marble Point

Figure 3.5: Rock outcrop and surrounding area at Gneiss Point field site prior to departure from site on 26th October 2002

There was some evidence of biological activity (Figure 3.6) as well as the presence of salt (Figure 3.7). However, analysis of samples returned to Christchurch after the fieldwork was only able to identify the presence of calcite.

Figure 3.6: Evidence of biological activity at Gneiss Point

Figure 3.7: Presence of salt beneath rock at Gneiss Point

The horizon diagram indicates that the horizon was relatively flat overall but that the sun would be below the horizon from the east through to the west at equinox as well as from the south-east in late February (Figure 3.8). These diagrams show when the rock surface is available to be heated by the sun.

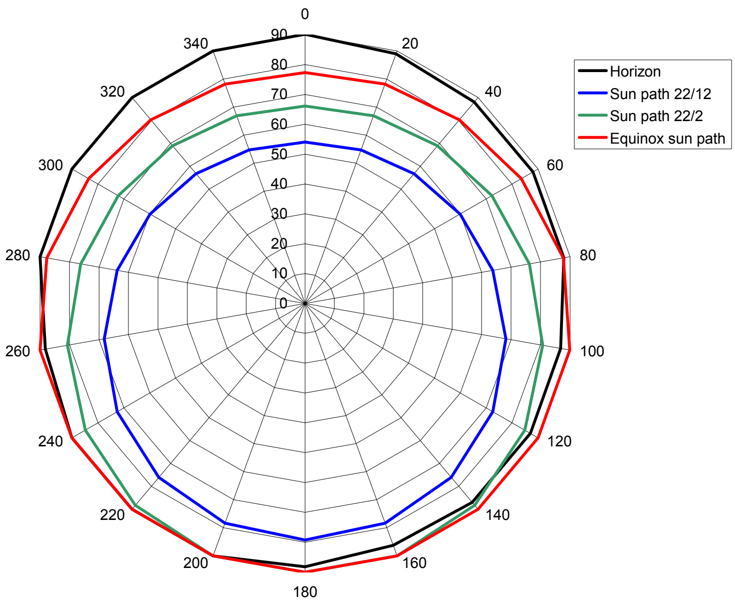


Figure 3.8: Horizon diagram for Gneiss Point field site

The outcrop chosen was approximately 7.8 m long by 6.1 m wide and 1.3 m high. One surface faced due south with an angle of inclination of 75^{O} (Figure 3.9A) and a second faced 260^{O} and was inclined at 63^{O} (Figure 3.9B). Figure 3.9 also shows the location of the equipment for each of the two aspects.

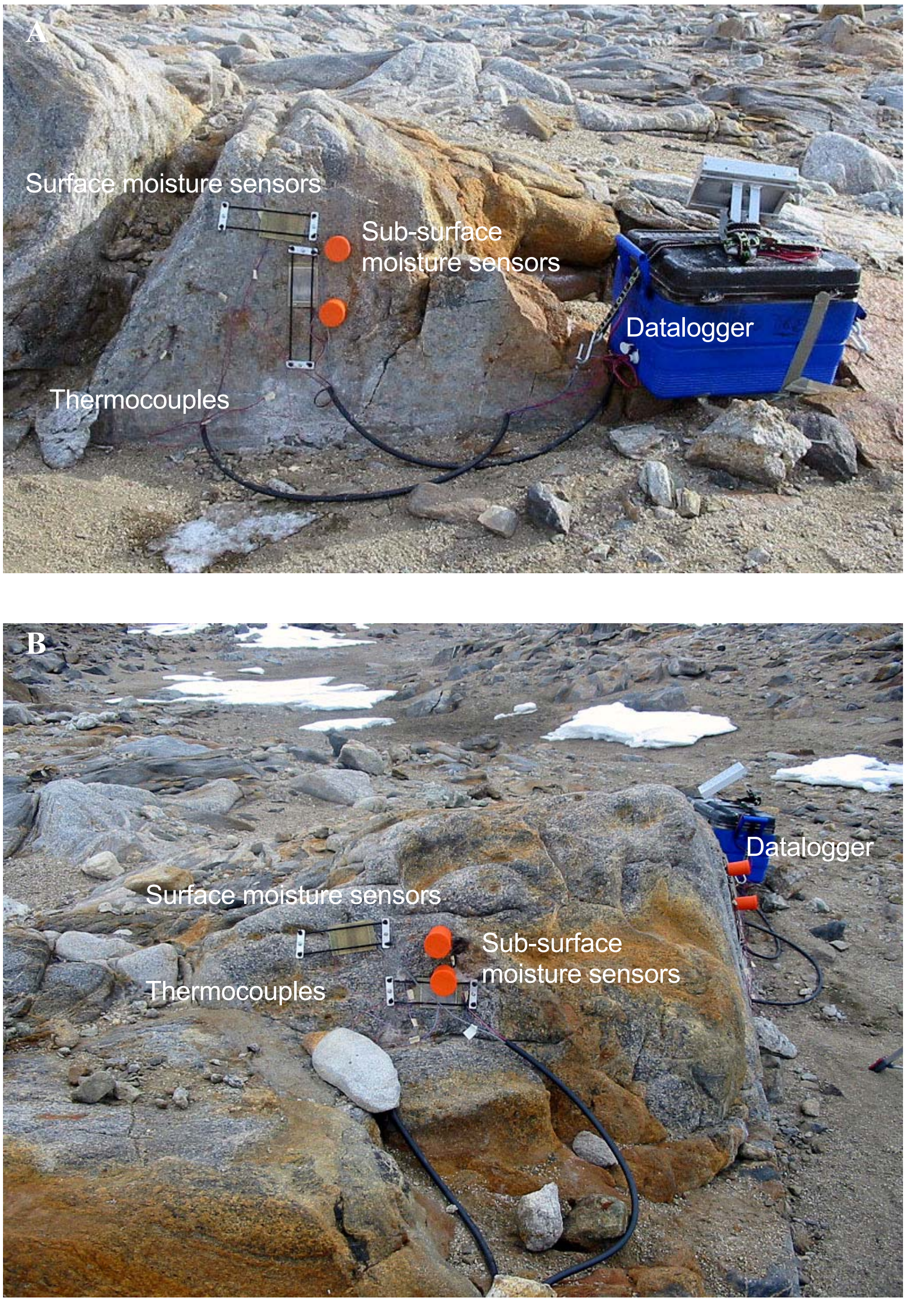


Figure 3.9: Gneiss Point field site showing placement of equipment, A. south-facing rock surface; B. west-facing rock surface

As shown in Figure 3.10, the research site was located within a small strip of Granite Harbour Intrusive granodiorite (lg) that is sandwiched between marble/schist (km) at the coast and gneiss (pg) inland.

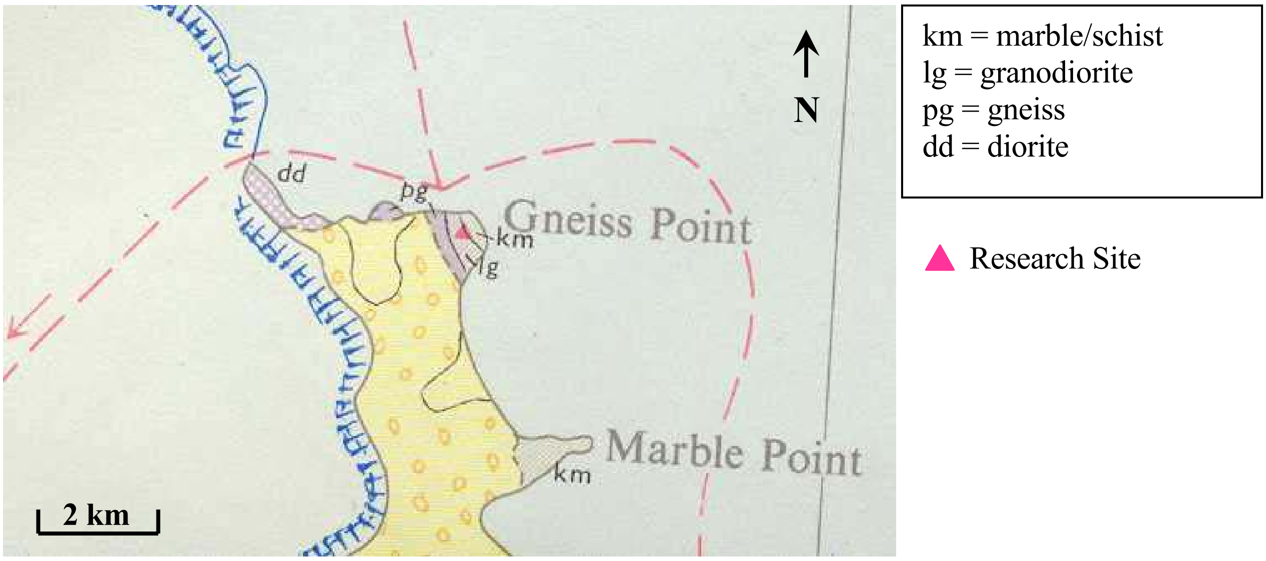


Figure 3.10: General geology of Gneiss Point area. Source: Gunn & Warren, 1962

The granodiorite is Larsen granodiorite, the only syntectonic granitoid of the Granite Harbour Intrusive complex. A potassium-argon date puts these granites at approximately 520 Ma (Goldich, Nier & Washburn, 1958 cited in Gunn, 1962), although date of exposure is not known. Gunn (1962) describes the syntectonic intrusives as weakly gneissic, probably emplaced in the closing stages of the Ross Orogeny as a single intrusion. Details of the rock itself are provided in Chapter 4.

3.3.2 Victoria Valley

The Victoria Valley (77^{O} 22'S, 162^{O}E) is the northernmost of the three main Dry Valleys of Victoria Land (Figure 3.11). The valley is oriented in a south-easterly direction, although the lower part of the valley near Lake Vida lies in a more easterly one (Figure 3.12). The Dry Valleys, first discovered during Scott's Discovery Expedition of 1901 to 1904, are named as such because they are protected from moist coastal air by Ross Island and the Royal Society Range on the one hand and glacial intrusion from the Transantarctic Mountains on the other (Chinn, 1990). Normally they are snow free as the air is so dry that any snow fall is evaporated before it reaches the ground. However, at the time of the first visit in October 2002 the valley was snow covered to a depth of about 15 cm, anecdotally the most snow the valley had experienced in decades. Again there was evidence of salt precipitation on the ground surface (Figure 3.13) but no biological activity was noted.

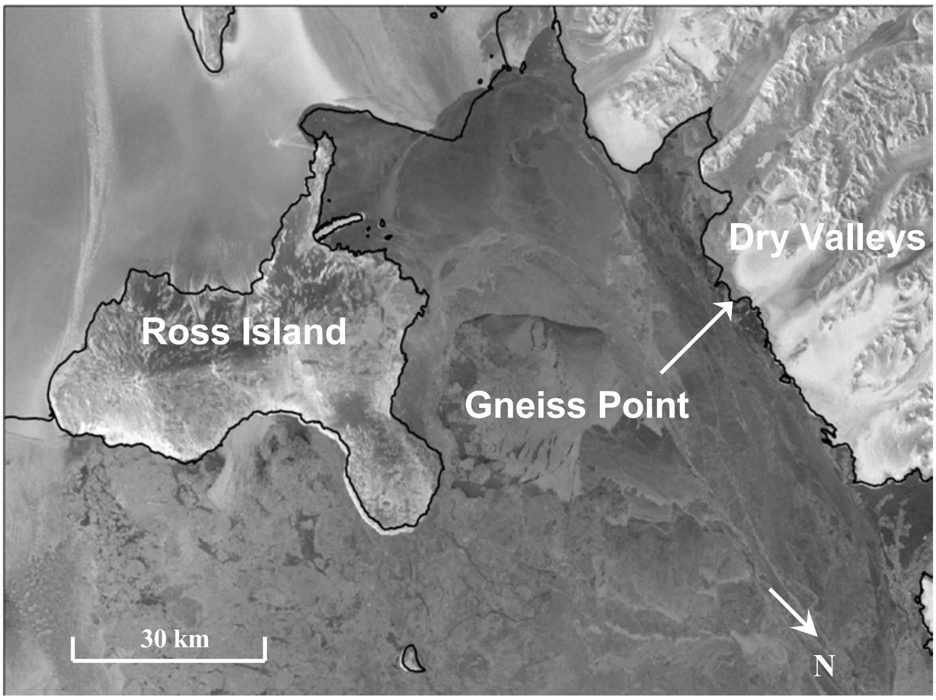


Figure 3.11: Location of Dry Valleys in relation to Ross Island

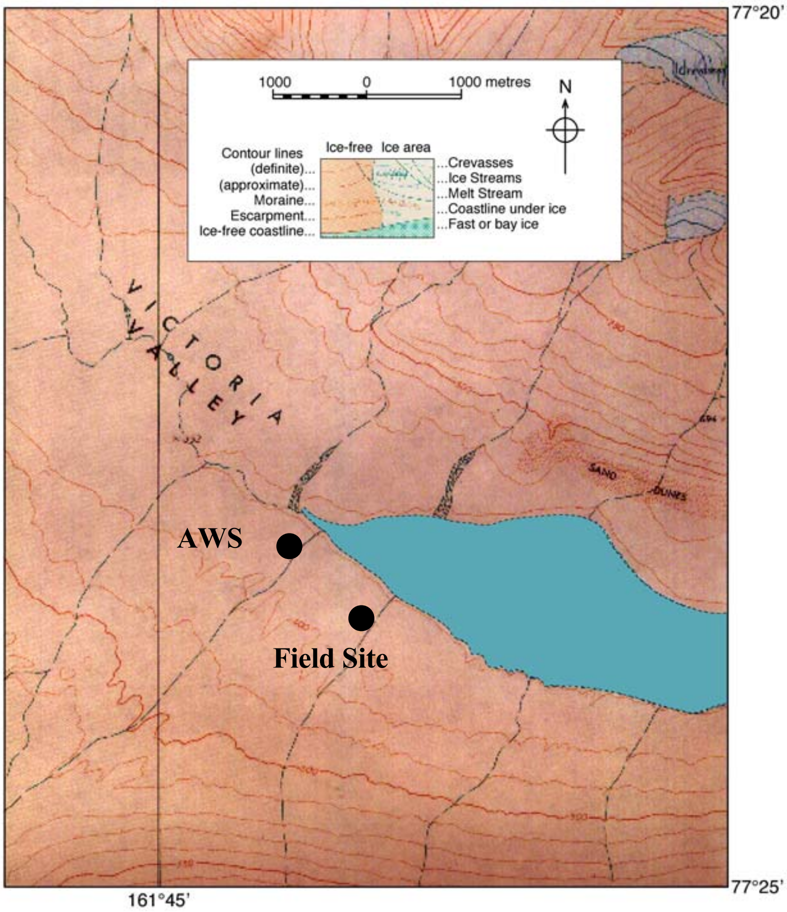


Figure 3.12: Location of Victoria Valley site in relation to Lake Vida, the automatic weather station and the ephemeral streams. Source: USGS 1:50 000 Topographic Series, Victoria Upper LakeQuadrangle

Figure 3.13: Evidence of salt near Lake Vida, Victoria Valley

The Victoria Valley is approximately 20 km long and contains two lakes, Lake Vida and Victoria Upper Lake (at the snout of the Victoria Glacier), both of which are perpetually frozen. It is glacier filled at either end. A number of ephemeral streams run into the lakes from the valley sides. An automatic weather station is located at the western most end of the lake (Figure 3.12). The field site (77^{O} 23'S and 161^{O} 55'E) was approximately three-quarters of the way down Lake Vida and 100 m from its southern shore. Two ephemeral streams ran either side of the site and there were clear views across the lake to the sand dunes and the St John Ranges. The ground surface was a mosaic of relatively flat rock outcrops and grus (Figure 3.14).

A large boulder and a flat piece of bedrock were chosen for the experimental work. The boulder was located 3 or 4 metres above the western-most stream bed and about 100 m from the lake edge. It was of irregular shape and approximately 1.4 m long by 0.6 m wide and 0.4 m high. The front edge, which contained the thermocouples and moisture sensors, faced to the NNE (23 ^{O}) with an 82^{O} slope to the N (Figure 3.15).

Figure 3.14: Location of Victoria Valley sites looking across Lake Vida to the St John Ranges and the sand dunes

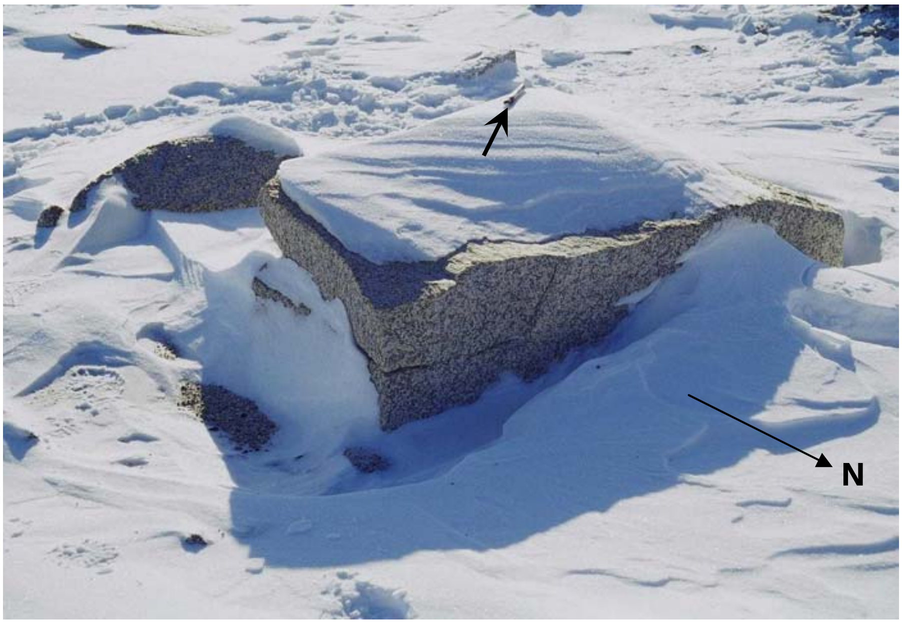


Figure 3.15: Victoria Valley north-facing rock outcrop. The pen on the snow surface is approximately 140 mm long

The second site was a horizontal piece of roughly rectangular bedrock on top of a small rise 100 m east of the north-facing site. One edge was approximately 2.9 m long whilst the other edge was 2.1 m in length (Figure 3.16).

Figure 3.16: Victoria Valley horizontal site. The pen in the centre of the block is approximately 140 mm long

The horizon diagram indicates that the sun would be below the horizon from the south during summer, extending to the south east to south west by late February (Figure 3.17).

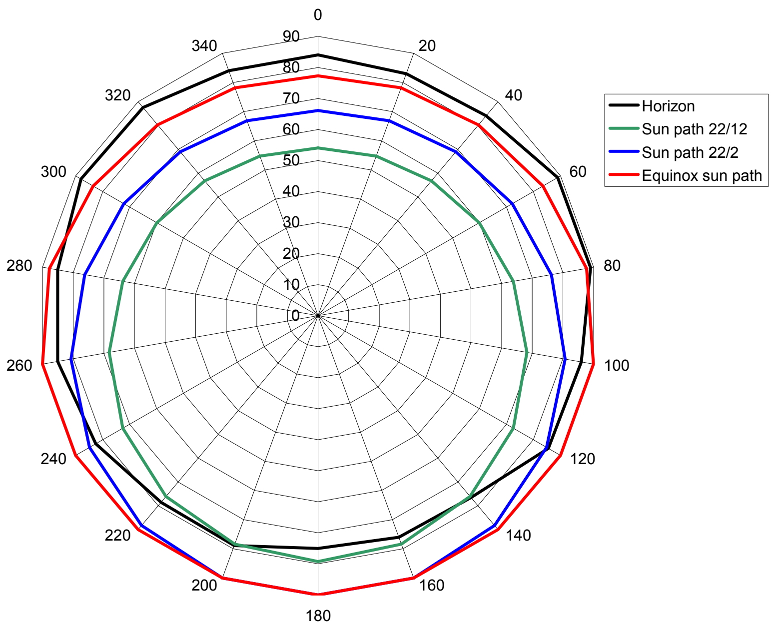


Figure 3.17: Horizon diagram for Victoria Valley site

The granite in that part of the Victoria Valley is from the Orestes pluton of the Granite Harbour Intrusive Complex. The pluton is ellipsoidal in shape and approximately 486 ± 14 Ma old (Stuckless & Erickson, 1975 cited in Turnbull et al., 1994). Vanda mafic and felsic dikes cut across the valley in a NE-SW direction (Figure 3.18). Chapter 4 provides details of the rock characteristics.

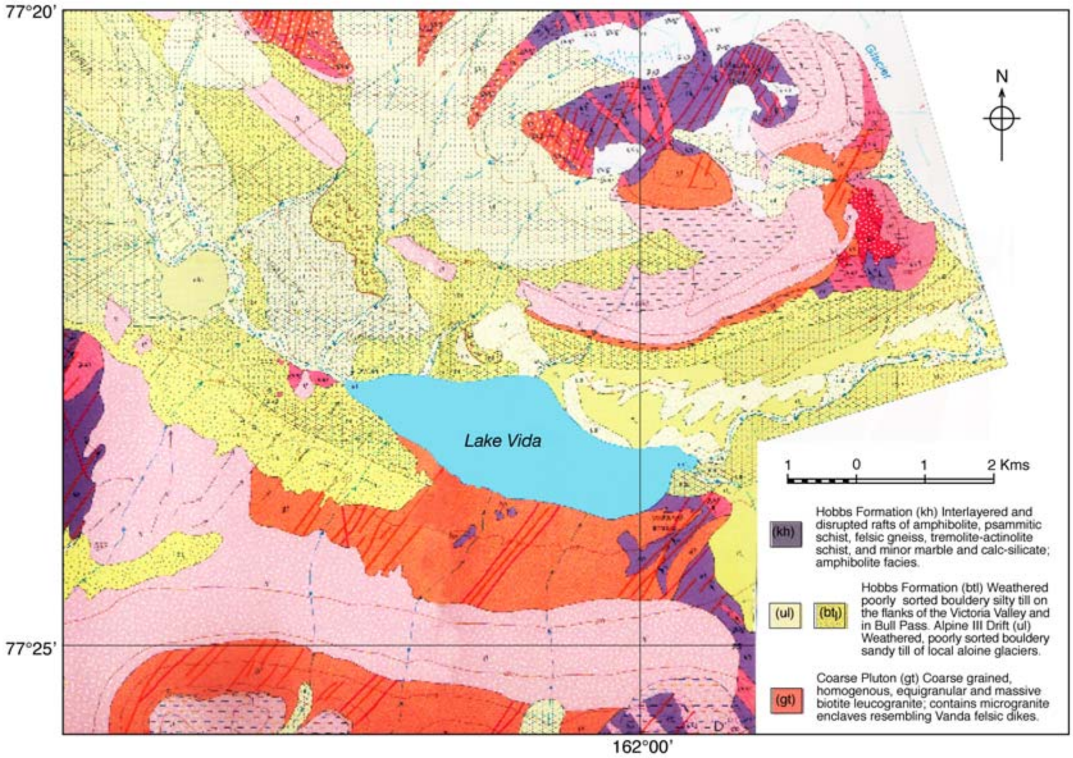


Figure 3.18: Geology of Victoria Valley in the vicinity of Lake Vida. Source: Turnbull et al., (1994)

3.3.3 TERRA NOVA BAY

The Italian Antarctic Station at Terra Nova Bay (164^{O} 07' E, 74^{O} 41'S) is situated slightly above sea-level on a peninsula oriented in a north-south direction (Figure 3.19). The (Eneide) AWS is located close by on a 90 m ridge approximately 200 m from the base. The area is characterised by massive granite outcrops, frequent tafoni and other weathering features (Figure 3.20). The sea ice usually melts for a substantial portion of each summer. Biological activity was evident below the surface of rocks (Figure 3.21) and the presence of salt was observed (Figure 3.22). Solar radiation produced snowmelt and small quantities of running water were noted on a number of occasions (Figure 3.23).

Figure 3.19: Location of Terra Nova Bay research site, automatic weather station and the general geomorphology of the area. Source: Baroni, 1987

Figure 3.20: Example of tafone found in Terra Nova Bay area

Figure 3.21: Evidence of biological activity found beneath surface of granite at Terra Nova Bay

Figure 3.22: Salt encrustations in weathering pit at Terra Nova Bay

Figure 3.23: Meltwater on rock surface at Terra Nova Bay

Two suitable research sites were identified on a ridge 100 to 120 m high approximately 25 minutes walk inland and south of the base (Figure 3.24). A small lake (Skua Lake) was located nearby. One site had a west facing aspect (274^{O}) and a surface inclination of 64^{O}. The outcrop was 18.2 m long, with its northern end being 4.8 m wide and 1.8 m high, whilst its southern end was 3.3 m wide and 2.3 m high. A persistent patch of snow was present along the length of the outcrop to approximately half way up the face (Figure 3.24). This snow showed clear evidence of melting and refreezing during the course of the experiment.

Figure 3.24: Location and general description of Terra Nova Bay field sites

The second site, which was very close by and slightly south of the first one, had a southern facing aspect (170^{O}) and a 66^{O} surface inclination. It was 7.4 m long and 2.9 m wide and 1.8 m high at its northern end but was 3.7 m wide and 1.9 m high at its southern end. A large deflation groove was located on its eastern side (Figure 3.25).

Figure 3.25: South facing Terra Nova Bay site showing deflation groove, note 30 cm ruler for scale

The horizon diagram indicates that the sun will be below the horizon from the south east to south west by the end of summer (Figure 3.26).

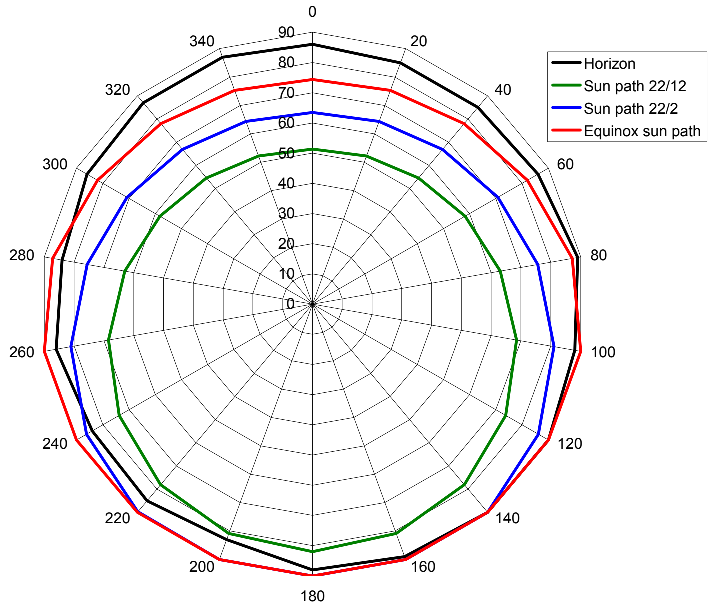


Figure 3.26: Horizon diagram for Terra Nova Bay field site

Abbott Granite forms the central mass of the Northern Foothills (Skinner, 1982) and is a different suite from those of southern Victoria Land (Figure 3.27). It was emplaced at approximately 508 Ma (di-Vincenzo & Rocchi, 1999).

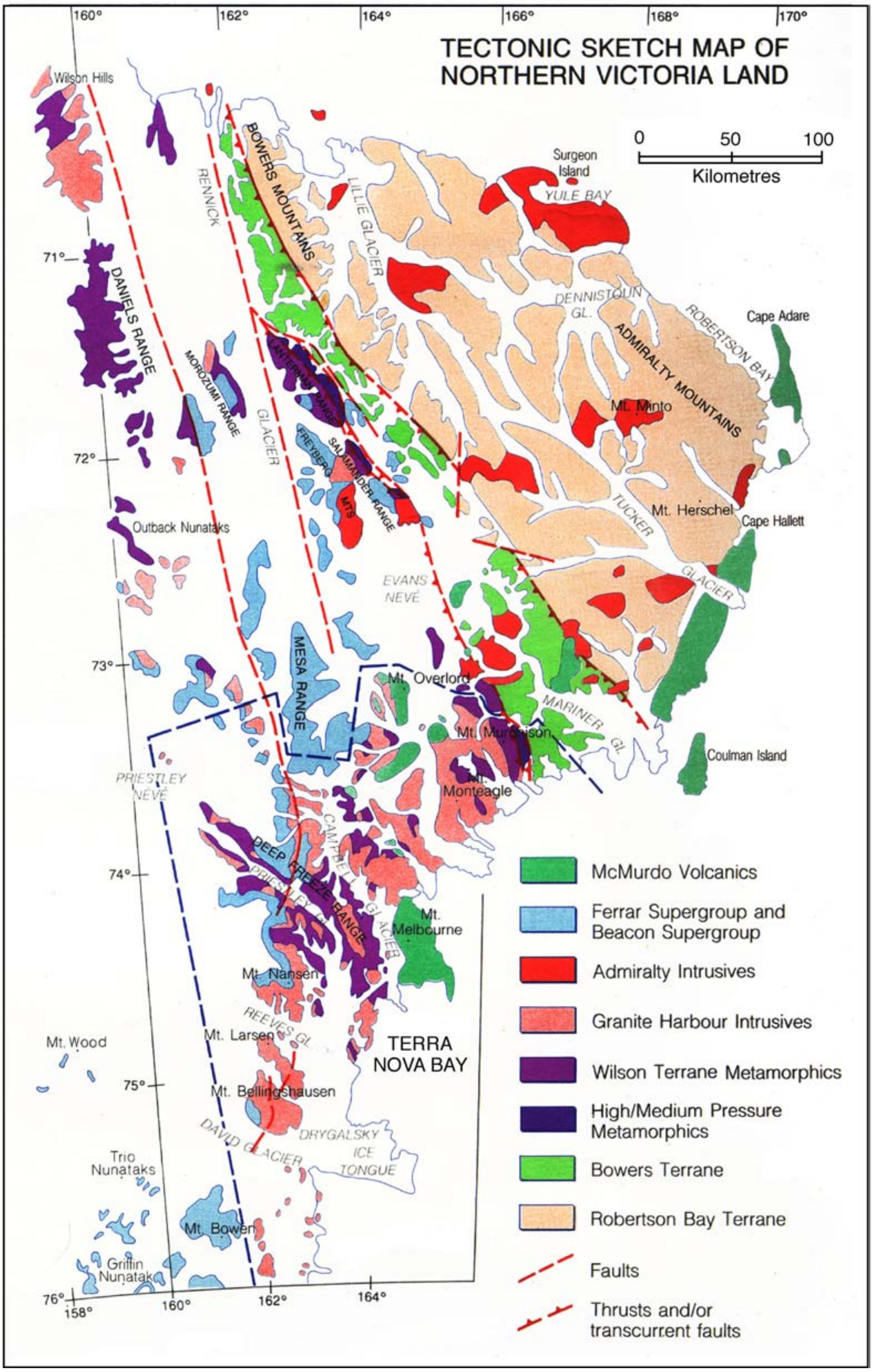


Figure 3.27: Geological Map of the Terra Nova Bay area. Source: Carmignani et al., 1987

3.3.4 TEALL ISLAND

Teall Island (79^{O} 03'S, 161^{O} 56'E) is a small island (12 km long by 7 km wide at its widest point) on the ice shelf just off the Victoria Land Coast between the Skelton Glacier outlet to the north and the Mulock Glacier outlet to the south (Figure 3.28). The island is steep sided with a peak of 661 m at its southern end and a high point of 468 m at its northern end. Mainly snow covered, it has an area characterised by many large boulder outcrops to the north (Figure 3.29). The nearest AWS is Marilyn (79^{O} 57'S, 165^{O} 23'E) located on the Ross Ice Shelf some 120 km south and 80 km east of Teall Island (Figure 3.3).

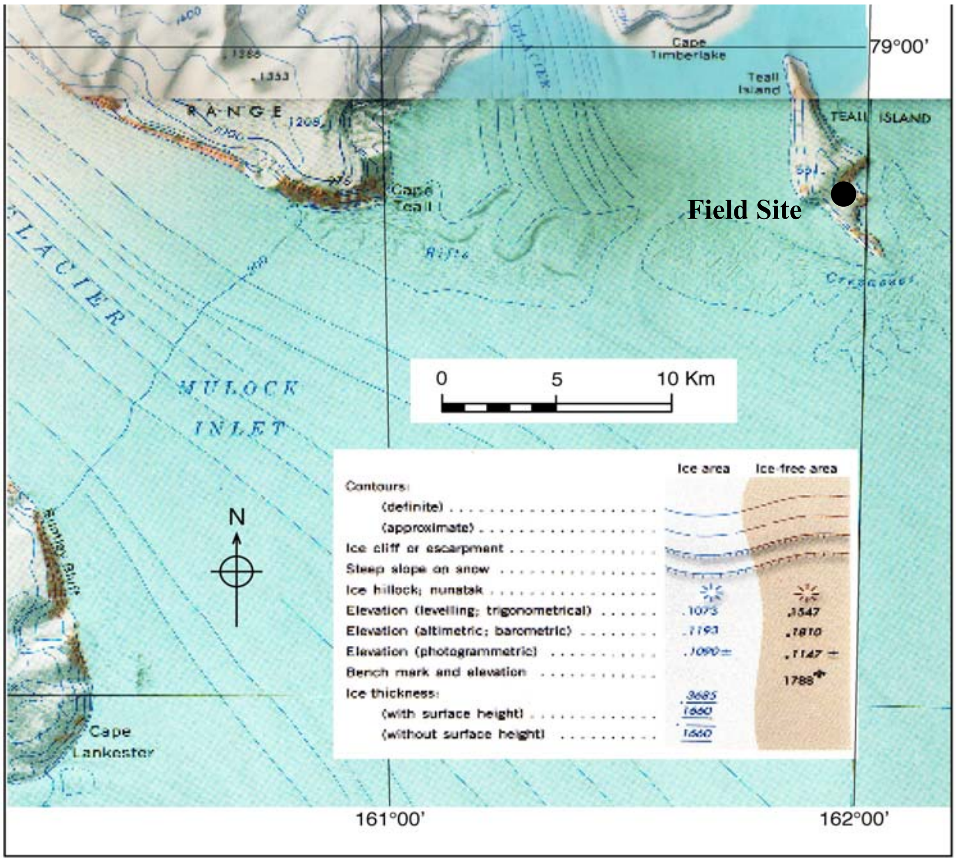


Figure 3.28: Location of Teall Island in relation to the Victoria Land coast. Source: compilation of USGS 1:250,000 Reconnaissance Series Carolyn Glacier and Mt Harmsworth

Precipitated calcite was evident on a number of rock surfaces (Figure 3.30) and the presence of lichen was occasionally noted. As for Terra Nova Bay there was evidence of small quantities of running water following heating by the sun (Figure 3.31).

Figure 3.29: Area around the Teall Island field site

Figure 3.30: Calcite precipitated onto surface of granite at Teall Island

Figure 3.31: Evidence of meltwater on granite following heating by sun at Teall Island

The field site was located near the col between the two high points (Figure 3.28) at an altitude of approximately 400 m. Two nearby outcrops were chosen for the experimental work: one with a southerly aspect and one with a westerly one. The west-facing outcrop was 1.6 m wide at its greatest point and 1.2 m high and faced 305^{O} (Figure 3.32). The surface had an inclination of 48^{O} and a biotite xenolith and scaling were evident.

Figure 3.32: West-facing Teall Island site showing location of equipment

The south facing aspect was approximately 1.26 m wide by 1.36 m high and contained a large crack near its lower left edge and a hollow on its right hand side. It faced 170^{O} with an inclination of 61^{O} (Figure 3.33).

Figure 3.33: South-facing Teall Island site showing location of equipment

Except in winter the sun does not dip below the horizon at this site (Figure 3.34).

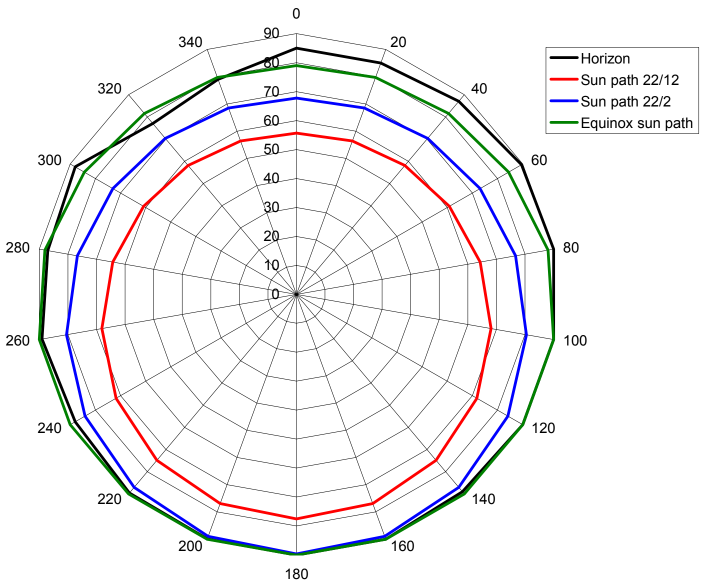


Figure 3.34: Horizon diagram for Teall Island field site

The research site was located on an outcrop of Skelton Granodiorite of the Granite Harbour Intrusive complex (Figure 3.35). According to Gunn and Warren (1962) this suite was post tectonic and emplaced after the Larsen Granodiorite of the Gneiss Point area and is similar in composition to those of the Victoria Valley area. However, more recent information places these rocks as older than those of the Larsen Granodiorite (pers.comm. S. Read). Details of the rock itself are given in Chapter 4.

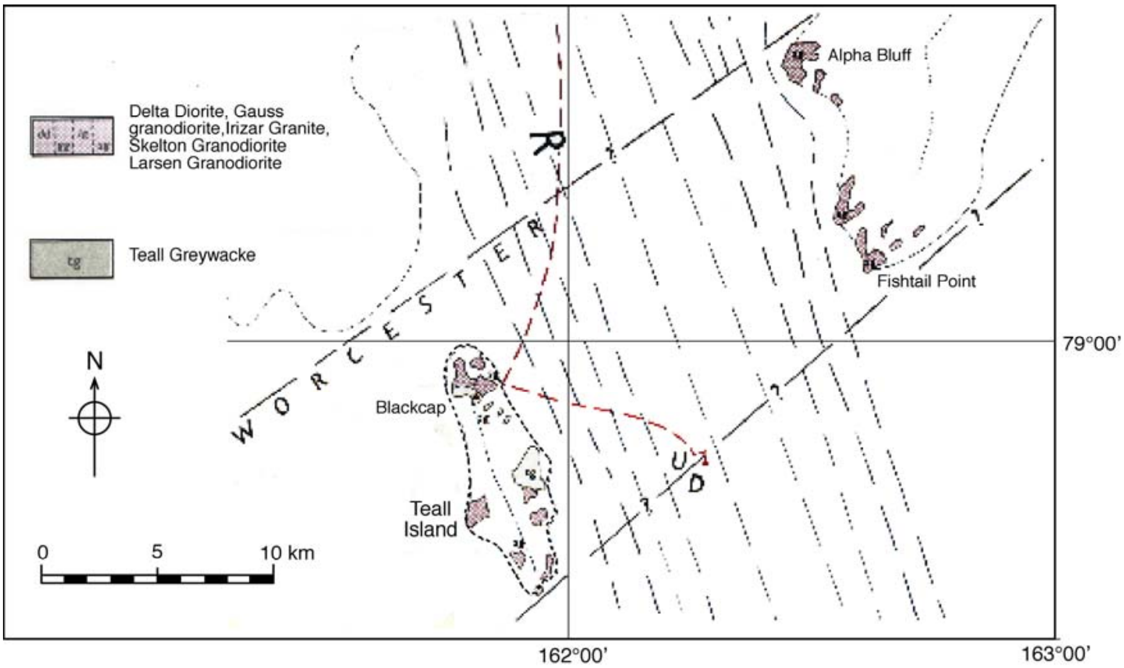


Figure 3.35: Geology of area around Teall Island field site. Source: Gunn & Warren, 1962

3.4 Rock Temperatures

3.4.1 Methodology

One millimetre diameter copper-constantan thermocouples (Appendix 1) were used to measure surface and subsurface rock temperatures. The surface thermocouples were attached using an epoxy glue (Appendix 1) and where possible, in an effort to maintain surface characteristics, they were covered in either rock flour or a small rock chip (Figure 3.36). However, weather conditions at the time of setting up and general wear and tear during the period of the experiment meant that placing rock flour or rock chips on the thermocouple head was mostly unsuccessful.

Figure 3.36: Example of surface thermocouple at Gneiss Point successfully covered by small rock chip (circled)

Although fast setting epoxy was used, the cold temperatures (both air and rock) meant that it often took a great deal of time as well as glue before the thermocouple was properly attached (Figure 3.37). A different type of epoxy, recommended as being more appropriate for these kinds of temperatures, was used in 2003/04 (Appendix 1). Unfortunately, this brand was not clear but opaque and quite dark in colour (Figure 3.38) and so was used only once in October 2003 at the west-facing Terra Nova Bay site. It was subsequently replaced in January 2004, prior to the winter temperatures being recorded. It is not known what effect this may have had on the surface temperatures, although previous studies suggest that daytime temperatures would be higher as a consequence (André et al., 2004)

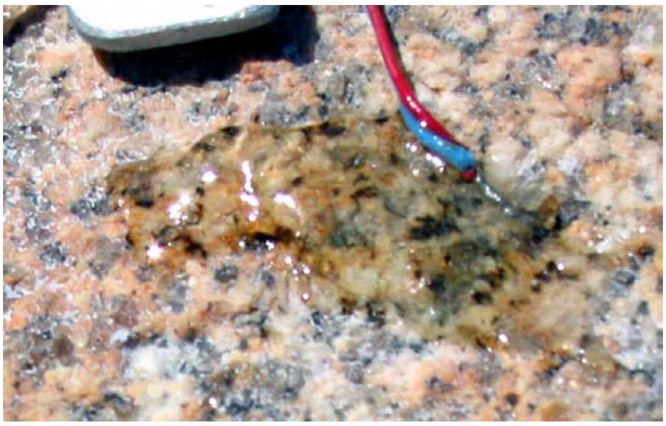


Figure 3.37: Surface thermocouple attached using clear araldite

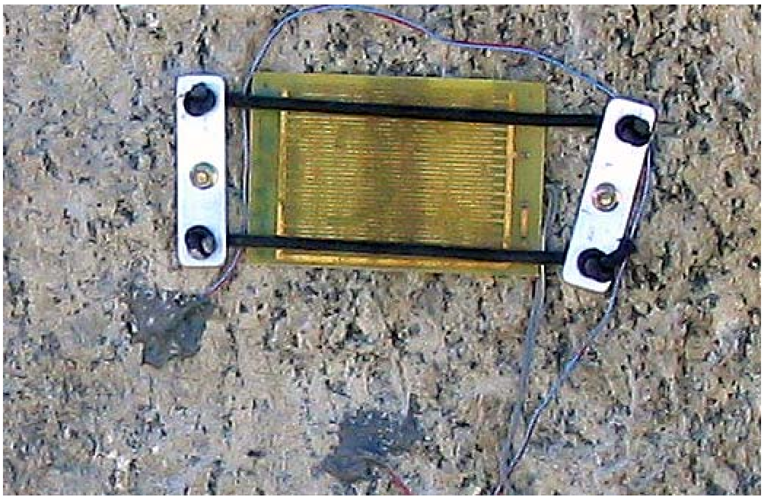


Figure 3.38: Surface thermocouples attached using opaque araldite at Terra Nova Bay site

Three surface thermocouples were used to ensure that at least one would remain functional for the full period of the experiment (labelled S1, S2 and S3). In fact, particularly in the second and third seasons, all three thermocouples usually remained attached to the rock. Where this was the case the three temperatures were averaged. Otherwise, and following examination in the field, the thermocouple (or thermocouples) which had remained closely attached to the rock surface was used.

Subsurface temperature was measured using the same type of thermocouples, which were inserted into 12 mm diameter holes drilled into the rock to 45 mm, 90 mm and 400 mm depths. Depths were chosen for comparison purposes with other research (e.g., 400 mm in Matsuoka, 1994) and the subsurface moisture measurements. The maximum depth possible for the latter was 90 mm and so this depth and half this depth were deemed appropriate (Section 3.6). The thermocouples were held in place by silicon rubber (Figure 3.39). All the thermocouples (surface and subsurface) were carefully labelled with weather proof material and secured by using either available rocks or small bolts and clips attached to the surface to hold them in place. In addition, lengths of tubing were used to protect the wires where this was deemed necessary (Figure 3.39).

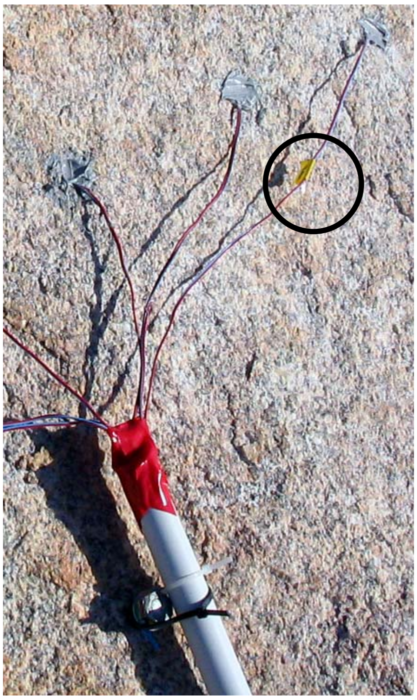


Figure 3.39: Subsurface thermocouples, label (circled) and attachment mechanism

The reference temperature for the thermocouples was provided by a Campbell Scientific 107 thermistor which was placed in a sealed chilly bin along with the datalogger and the batteries. This means of providing the reference temperature (i.e. by not maintaining it at a steady temperature) introduced an error of ± 1 ^{O}C in the thermocouples at the temperatures being experienced (advice from Campbell Scientific). Surface temperatures were used to determine the temperature cycles for the laboratory simulations (Chapter 5) and the subsurface temperatures to estimate thermal diffusivity, as well as conductivity and thermal admittance at the different depths (Chapter 4).

3.4.2 Key Results

Figure 3.40 shows the surface and subsurface temperatures for the Gneiss Point south-facing site between 26th October 2002 and 18th January 2003. This illustrates the diurnal variation in temperature at the different depths as well as a general seasonal trend. The surface temperatures are generally below zero during the early part of the season but above zero in the latter part. Temperature fluctuations of several degrees occur even at 400 mm. The sudden cold period around the 16th November (circled) appeared to coincide with increased wind speed and wind direction changing to the south. It is not known whether cloud cover also changed during this period.

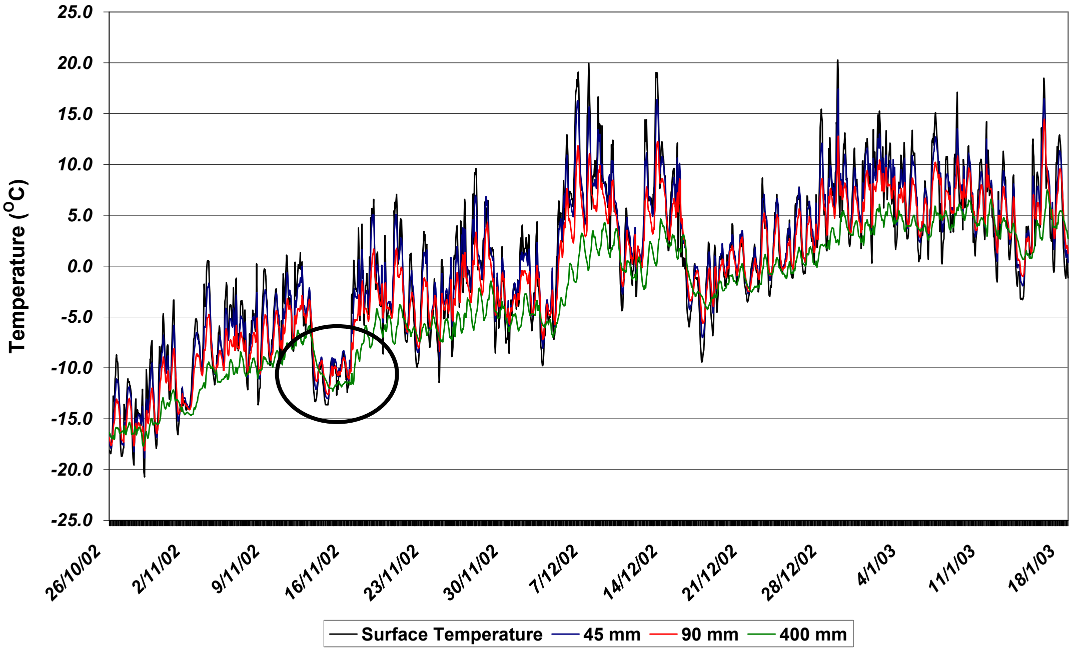


Figure 3.40: Gneiss Point south-facing site surface and subsurface rock temperatures 26th October 2002 to 18th January 2003. The circle highlights the sudden cold period referred to in the text

Figure 3.41 shows the temperatures recorded by the three surface thermocouples at Terra Nova Bay west-facing site between 14th November 2003 and 14th January 2004. The thermocouples were placed at slightly different heights on the rock surface and the damped oscillations of S1 and S3 indicate they were buried in snowdrift for a significant part of this period (and had to be excavated in January 2004). Despite this there were frequent crossings of the 0 ^{O}C isotherm. The exposed surface thermocouple, S2, had a maximum daily temperature range of approximately 20 ^{O}C during this period.

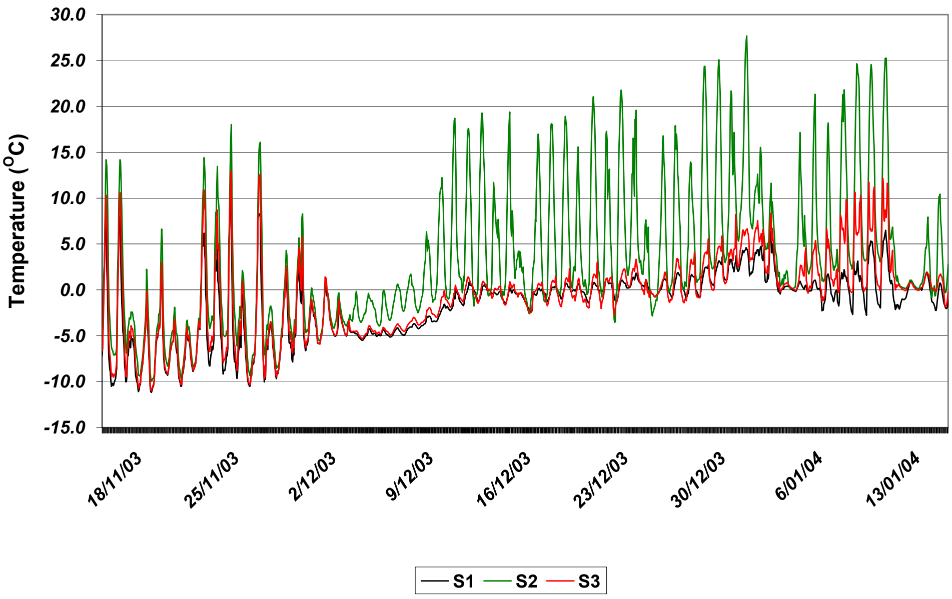


Figure 3.41: Surface temperatures at the Terra Nova Bay west-facing site showing suppressed oscillations for S1 and S3 during the period they were buried in snowdrift and the daily temperature range of the exposed thermocouple at S2

Contrary to expectations, there was considerable variability in rock temperatures over the winter months (Figure 3.42). A fluctuation of up to 25 ^{O}C could occur over the space of a couple of weeks. The close correspondence of the temperatures regardless of depth or aspect during the winter months is also apparent (Figure 3.42 A & B).

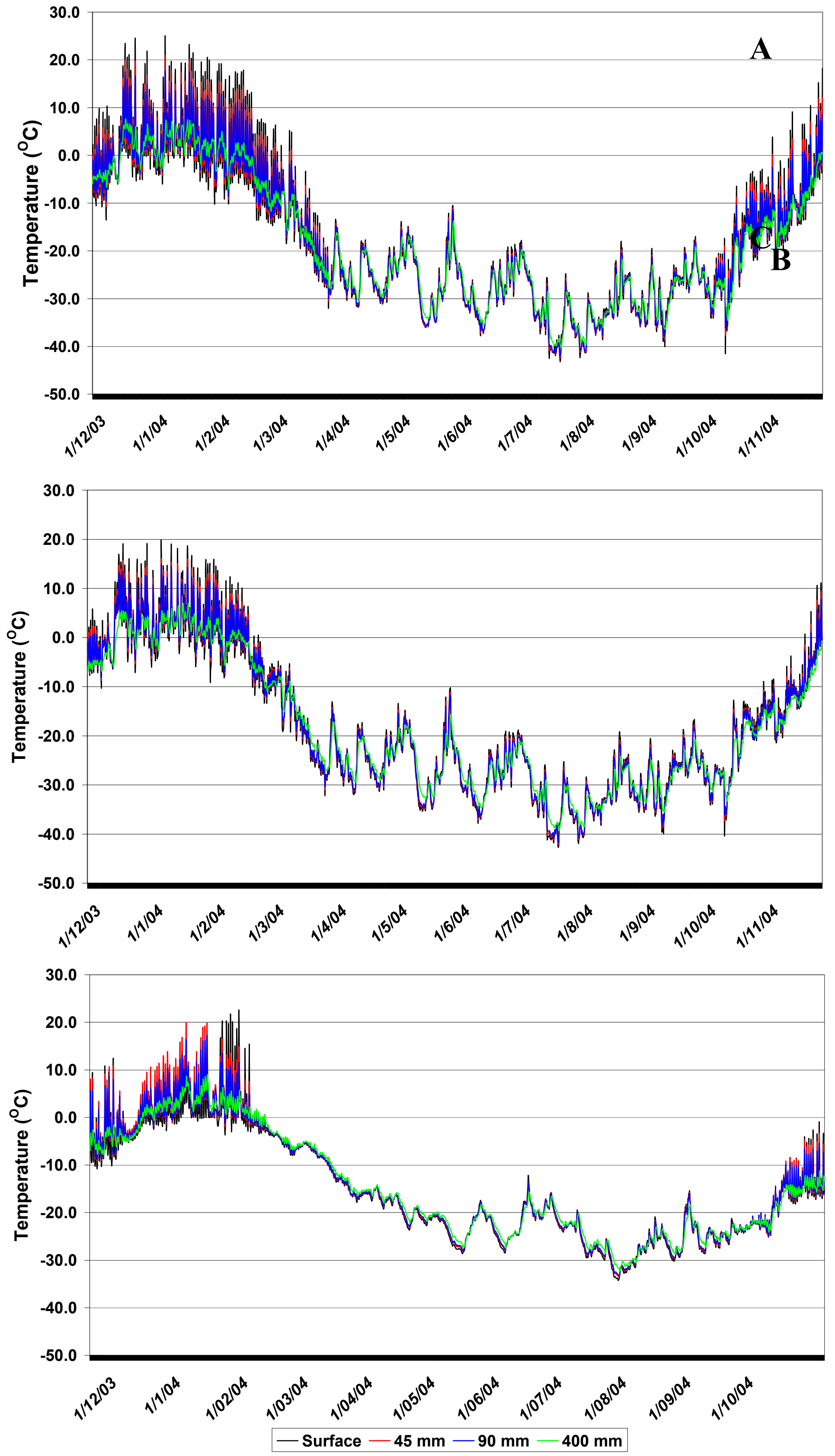


Figure 3.42: Rock surface and subsurface temperatures between November 2003 and November 2004 highlighting the considerable variability in rock temperatures during the winter period (A) Teall Island west-facing; (B) Teall Island south-facing and (C) Terra Nova Bay west-facing

A comparison of the west-facing rock surface temperatures at Terra Nova Bay and Teall Island shows that, although the Teall Island temperatures were usually lower than those at Terra Nova Bay (approximately 4.5^{O} of latitude further north), there was some correspondence in the pattern of variability indicating that macro-scale climatological processes at least play a role in winter rock temperature variability (Figure 3.43).

A comparison of the air temperature, rock surface temperature and wind speed and direction indicated that the winter rock surface temperatures were driven by air temperatures which in turn coincided with increased wind speeds and warm (foehn) or cold (katabatic) winds from the west (Figure 3.44). The effect of foehn winds has received little attention in Antarctic studies (pers.comm H. McGowan).

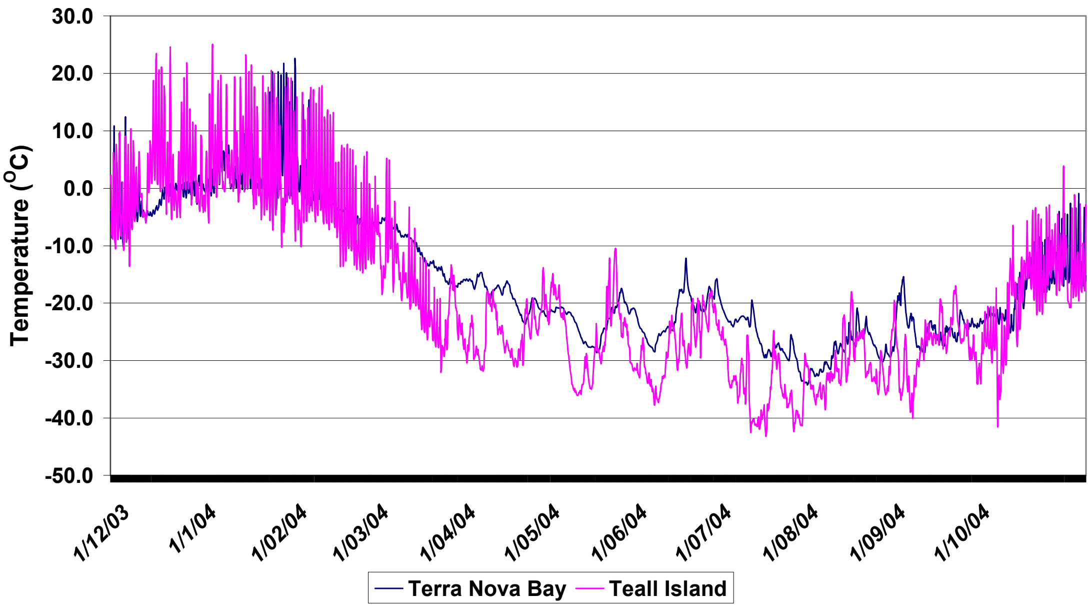


Figure 3.43: Comparison of Terra Nova Bay and Teall Island rock surface temperatures between November 2003 and November 2004 highlighting both the variability in winter temperatures at both sites as well as some correspondence in the winter pattern despite the 4.5^{O} latitudinal difference

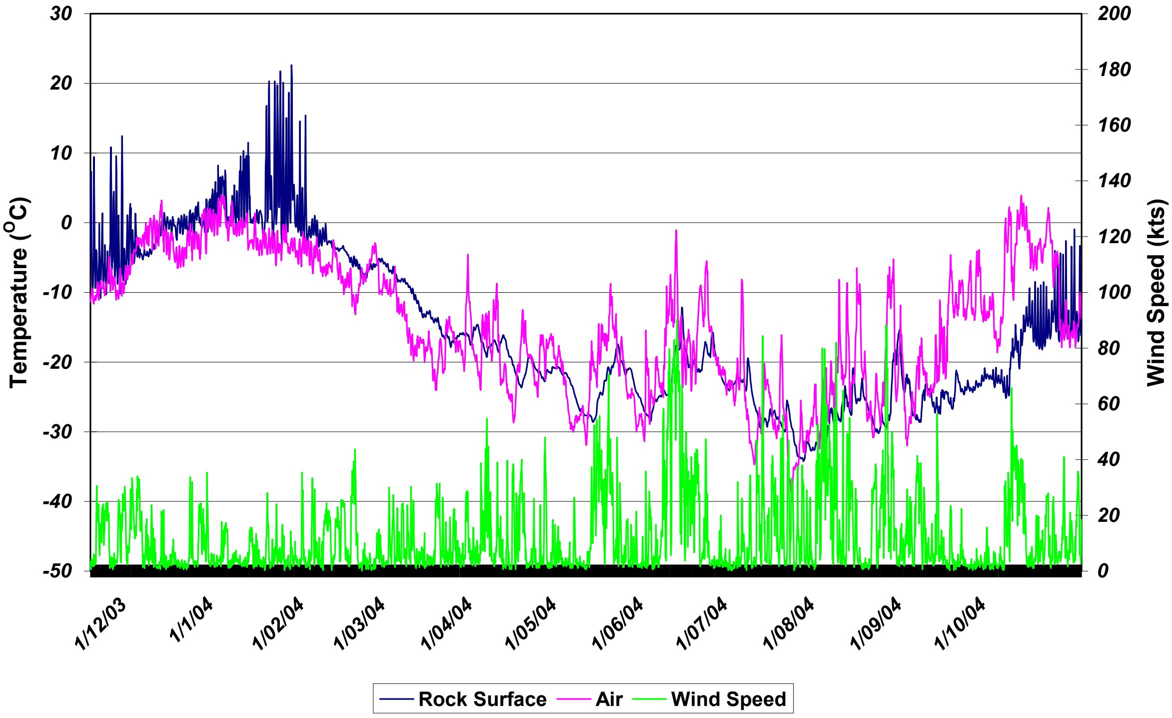


Figure 3.44: Air temperature, rock surface temperature and wind speed at the Terra Nova Bay west-facing site

An examination of the 45 mm subsurface temperatures at Teall Island shows that the two aspects had different temperature regimes at this depth during the spring/summer and autumn periods but not over the winter (Figure 3.45). Even at 45 mm depth the daily temperature range within the rock could be up to 20 ^{O}C and there were frequent crossings of the 0 ^{O}C isotherm during the summer months. Annual average subsurface temperatures were similar regardless of depth (-17.8 ^{O}C; -17.9 ^{O}C and -18.4 ^{O}C at 45 mm, 90 mm and 400 mm respectively), as were the minima (-42.4 ^{O}C, -42.0 ^{O}C and -40.1 ^{O}C respectively) but there were significant differences in the maxima: 20.9 ^{O}C, 17.6 ^{O}C and 7.7 ^{O}C respectively.

The 45 mm and 90 mm temperatures showed some correspondence with the surface measurements but not with the 400 mm depth ones. There was also some evidence of a time lag (Figure 3.46).

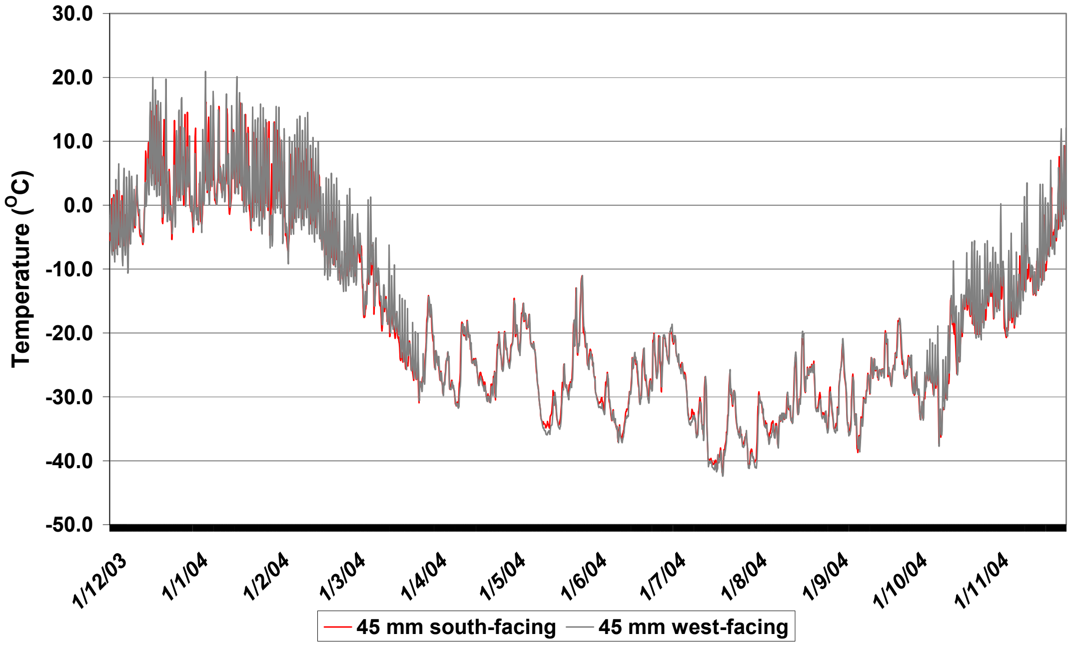


Figure 3.45: 45 mm depth temperatures at Teall Island showing the different patterns for the two aspects in the spring/summer and autumn but close correspondence in winter

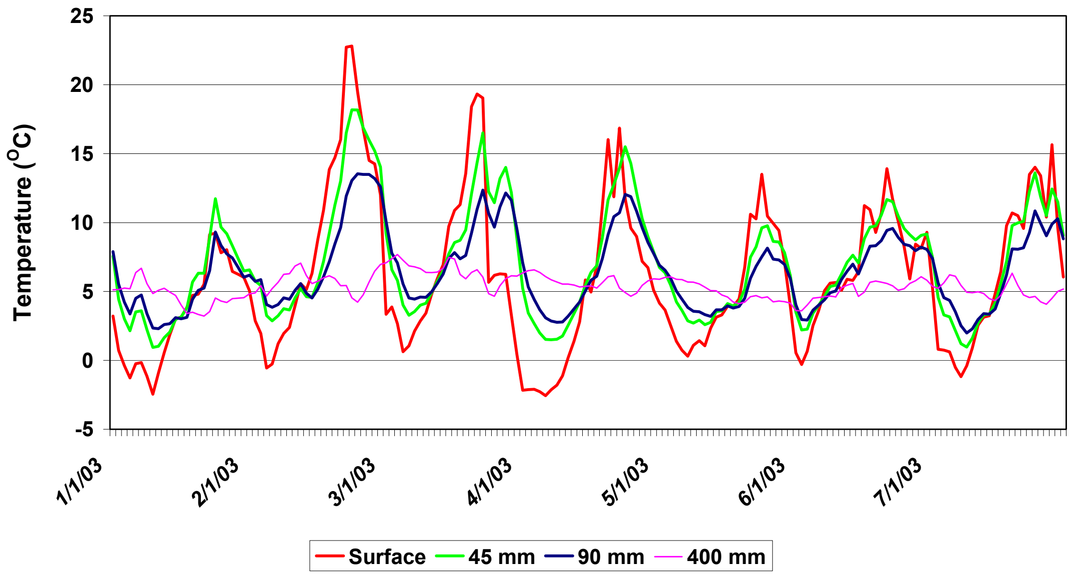


Figure 3.46: Surface and subsurface rock temperatures at Gneiss Point west-facing site between 1st and 7th January 2003 indicating the decreased amplitude with depth and evidence of a time lag between the surface and 45 mm and 90 mm depth measurements

Table 3.2 gives the number of occasions when surface temperature gradients exceeded 2 $^{O}C\ min^{-1}$ (there were no instances when this temperature gradient was exceeded for the subsurface temperatures). These are maximum figures as there were both seasonal as well as thermocouple differences in the numbers of occasions when the gradient was greater than the accepted threshold. Although these rapid changes in temperature occurred relatively infrequently, there was considerable variability from year to year and there were generally more instances on the west-facing aspect. It is not known how many might have occurred over the summer season as a whole.

Table 3.2: Maximum number of occasions when the rock surface temperature gradient was greater than 2 ^{O}C min^{-1} during a 48 hour period

Location	**Aspect**	**Maximum Number of Occasions in a 48 Hour Period per Season** [5]		
		2002/03	**2003/04**	**2004/05**
Terra Nova Bay	**S**	N/A	3[2]	3[4]
	W	N/A	8[3]	3[4]
Gneiss Point	**S**	1[1]	N/A	1[4]
	W	6[1]	N/A	2[4]
Teall Island	**S**	N/A	1[2]	6[4]
	W	N/A	2[2]	9[4]

[1] January 2003; [2] November 2003; [3] January 2004; [4] November 2004; [5] In this context season refers to the Antarctic summer field season, approximately late October to late January each year
N/A Not available

The number of freeze-thaw cycles varied with aspect and definition of a freeze-thaw event so that the west-facing aspect had approximately twice the number compared to the south-facing aspect at Gneiss Point (Table 3.3). There were also more than twice as many freeze-thaw events regardless of aspect using the definition of Fahey & Lefebure (1988) compared to the effective freeze-thaw cycles as defined by Matsuoka (1990b). Fahey & Lefebure (1988) defined a freeze-thaw event as one where the temperature crossed the 0 ^{O}C isotherm in both directions regardless of intensity but Matsuoka (1990b) defined an effective freeze-thaw cycle as one where the temperature must go below -2 ^{O}C through zero to + 2 ^{O}C.

Table 3.3: Freeze-thaw events at Gneiss Point between 26th October 2002 and 18th January 2003

	Number of Cycles	
	South-facing Aspect	**West Facing Aspect**
Freeze-thaw cycles[1]	47	85
Effective freeze-thaw cycles[2]	16	34

[1] As defined by Fahey & Lefebure (1988); [2] As defined by Matsuoka (1990b)

3.5 SURFACE MOISTURE

3.5.1 Methodology

Surface moisture was measured using sensors that detect the presence of liquid moisture (Appendix 1, Figure 3.47). The sensor consists of a continuous loop of aluminium on a flat, rectangular board 11.5 by 7.5 cm and has a track spacing of 1 mm. The narrow track spacing means that the sensor can detect even the smallest amounts of moisture reaching the rock surface. The sensor responds to the presence of liquid water by recording conductivity and a zero value is given if there is either no moisture present or if the surface is frozen (Elliott, 2004).

The sensors were attached to the Campbell CR 10X datalogger and the data collected at the same frequencies as the temperature measurements. With the exception of Victoria Valley (where glue was used due to problems with the drill) the sensors were attached to the surface of the rock using small bolts and straps. Two sensors were attached to the rock at each aspect to ensure at least one would operate for the full extent of the experiment (Figure 3.47). In fact, all sensors remained in place and operated throughout the field work.

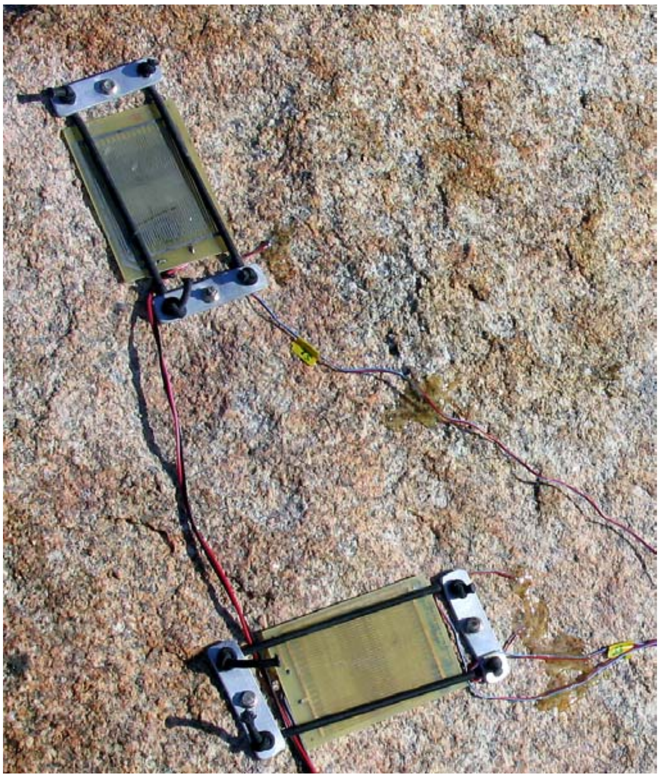


Figure 3.47: Surface moisture sensors attached to rock at Teall Island

3.5.2 Key Results

Sensor results are given in mV (a measure of conductivity) and, although these do not give actual quantities of moisture they do indicate when surface moisture events occurred as well as their relative magnitude. A surface wetting event begins when the moisture sensor records a value greater than zero and ceases when the sensor measurement returns to zero again. Elliott (2004) described the results for Gneiss Point, Victoria Valley and Terra Nova Bay for the 2002/03 and 2003/04 seasons and concluded that the surface of the rock was wetted more frequently than might previously have been supposed, even during periods of negative surface temperatures. It was also found that the Gneiss Point and Victoria Valley rock surfaces were wetted (on average) more frequently during the summer months than Terra Nova Bay (Elliott, 2004; Table 1) and that the surface wetting events differed in magnitude, time and duration with both aspect and location (Elliott, 2004; Figures 3, 4, & 5). At Terra Nova Bay west-facing site surface moisture was apparent throughout most of the 2003/04 year whereas at Teall Island moisture events were confined almost entirely to the months of November and December (Figure 3.48).

In addition, the length of time that the surfaces were wetted during the summer could be up to 40% of the time but this also differed with aspect and location as did the maximum length of time that surfaces were continually wetted (Elliott, 2004; Table 2). The proportion of short wetting events (defined as less than or equal to 8 hours) also varied from site to site (Elliott, 2004; Figure 6).

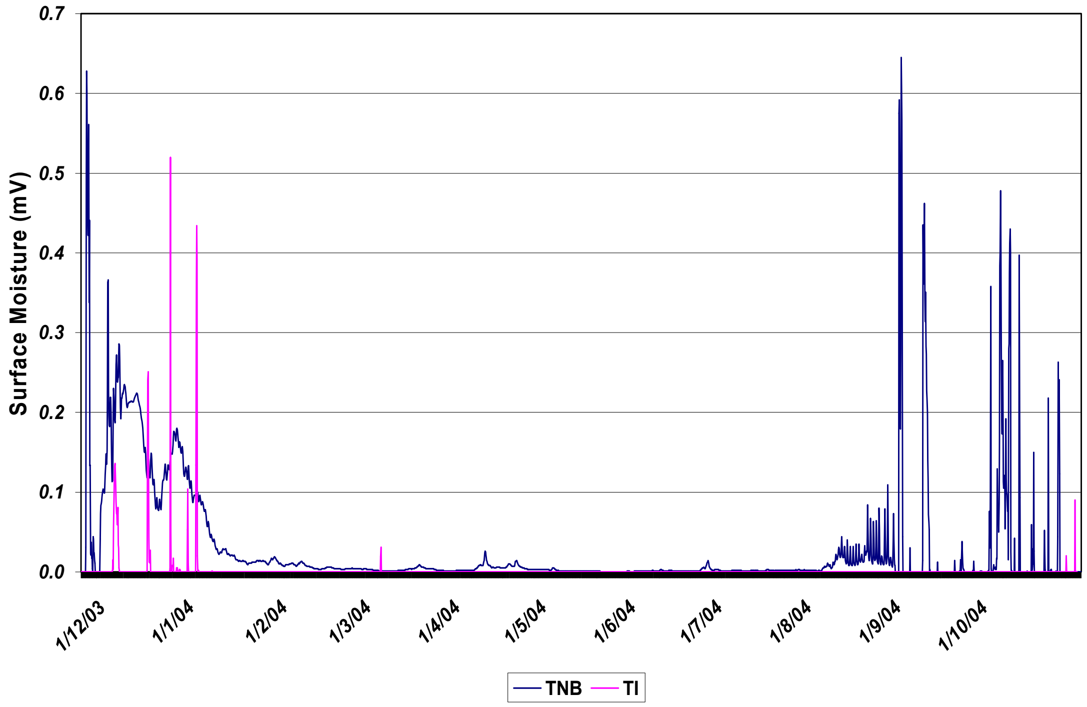


Figure 3.48: Surface moisture variability at Terra Nova Bay and Teall Island west-facing sites between 20th November 2003 and 18th November 2004

3.6 Subsurface Moisture

3.6.1 Methodology

The vapour density or actual moisture within the rock was measured using a Vaisala Relative Humidity Probe (HMI41) originally designed to measure moisture in concrete (Appendix 1, Figure 3.49).

Figure 3.49: The relative humidity equipment used during the experiment

Sixteen millimetre holes were drilled into the rock to 45 mm and 90 mm depths (the maximum operational depth of the probe) and the probes inserted. Plastic tubes isolated the probes from the rock for the length of the hole and the end was sealed with a small plastic bung (Figure 3.50A). Plastic cups and caps were then placed over the hole and probe to protect them from the weather (Figure 3.50B). These were labelled with a number to coincide with each probe (which were individually calibrated) and the depth to which they were to be inserted (Figure 3.49).

The tip of the probe was made of a moisture sensitive polymer and before readings could begin the probes were left sufficiently long to enable the moisture in the rock and the moisture in the small air pocket surrounding the tip of the probe to equilibrate. The equipment measures the relative humidity (%), temperature (^{O}C) and dewpoint temperature (^{O}C) of the air pocket. Actual vapour density was calculated using an empirical formula (Lowe, 1977). The general weather conditions were also recorded at the same time as the relative humidity readings which were made manually every 4 hours at each site during the times of actual visits, although the October/November 2002 readings were only made every 4 hours during the 'day'. The length of time of recording varied from visit to visit but ranged from a minimum of 48 hours to a maximum of 120 hours.

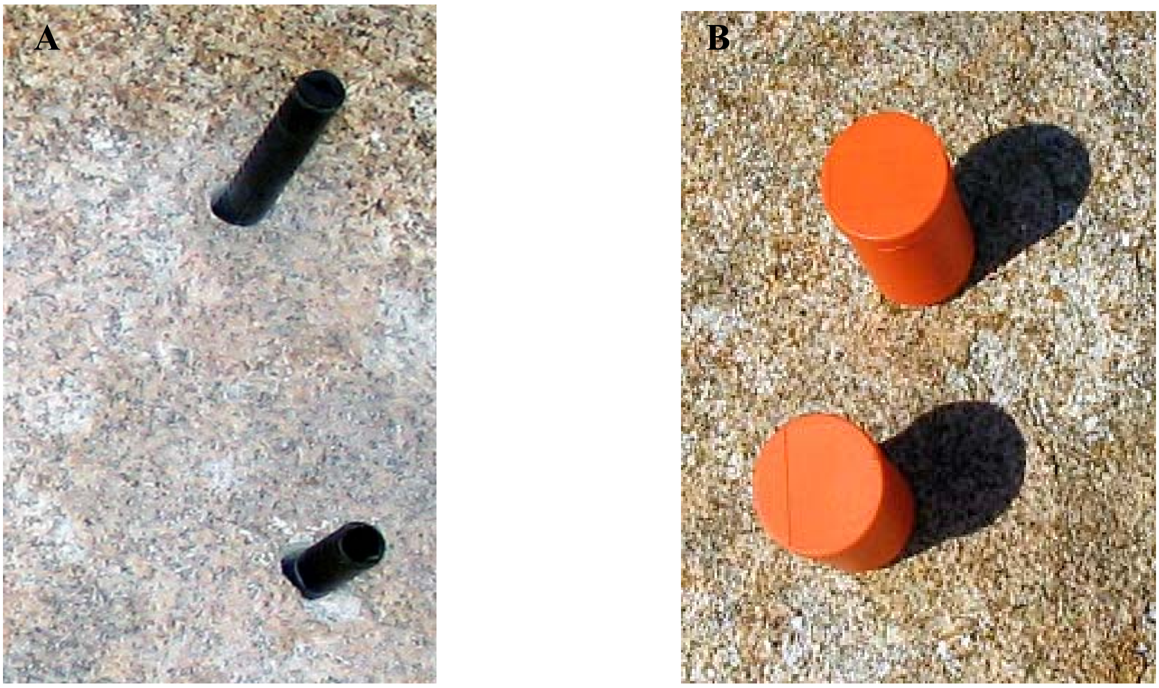
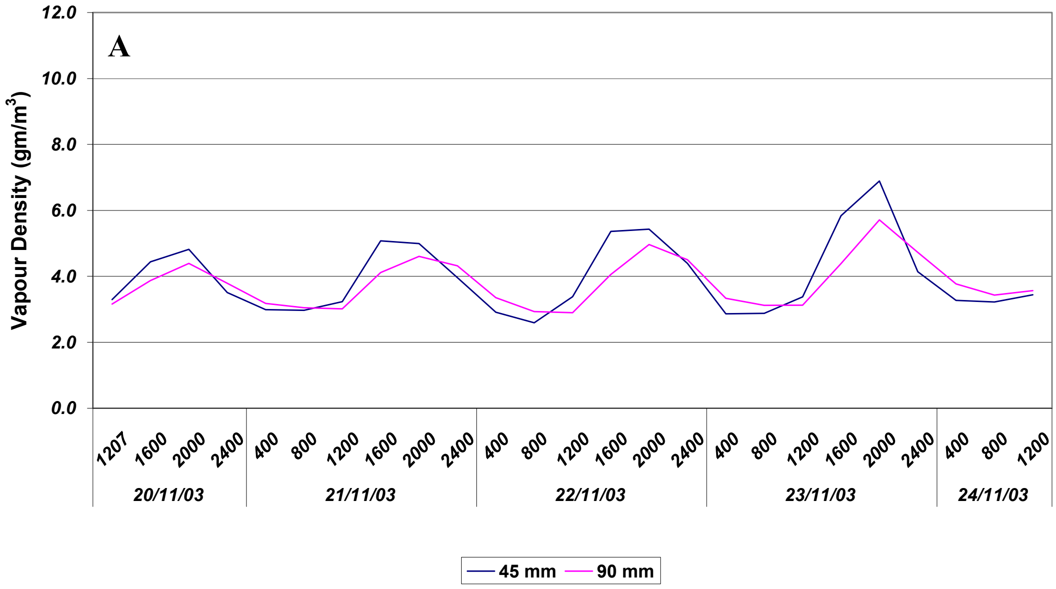


Figure 3.50: A. Plastic sleeves and bungs that isolate the probes from the rock surface and the atmosphere, B. The external plastic cups and caps in place in the field at Teall Island

3.6.2 Key Results

The 45 mm and 90 mm subsurface rock moisture varied with time of day and depth. The November 2003 Teall Island west-facing readings confirmed the findings from the 2002/03 season that there was a lower amplitude in the 90 mm depth moisture levels compared to the 45 mm ones as well as a time lag (Figure 3.51A). At times the 45 mm depth moisture levels were greater than the 90 mm ones but at other times they were less (Figure 3.51A). However, this was not always the case, as the November 2004 Terra Nova Bay south-facing site results indicate (Figure 3.51B). Figure 3.51 also shows that there can be considerable differences in subsurface moisture levels between latitudes, although it should be noted that the Teall Island measurements were made in November 2003 whilst those at Terra Nova Bay were from the following season.

Subsurface moisture differed with aspect and weather conditions (Figure 3.52). The appearance of wind together with cirrus cloud on the 21st November 2004 produced negative rock temperatures and resulting reduction in moisture within the rock. Seasonal differences in subsurface moisture are also apparent and Figure 3.53 compares the Teall Island west-facing site subsurface moisture regimes for the 20th to 22nd November 2003 and 2004. This shows that moisture levels in the latter year were approximately twice those in the same period 12 months earlier but that the appearance of cool winds and lower temperatures on the 21st November 2004 resulted in very similar levels.



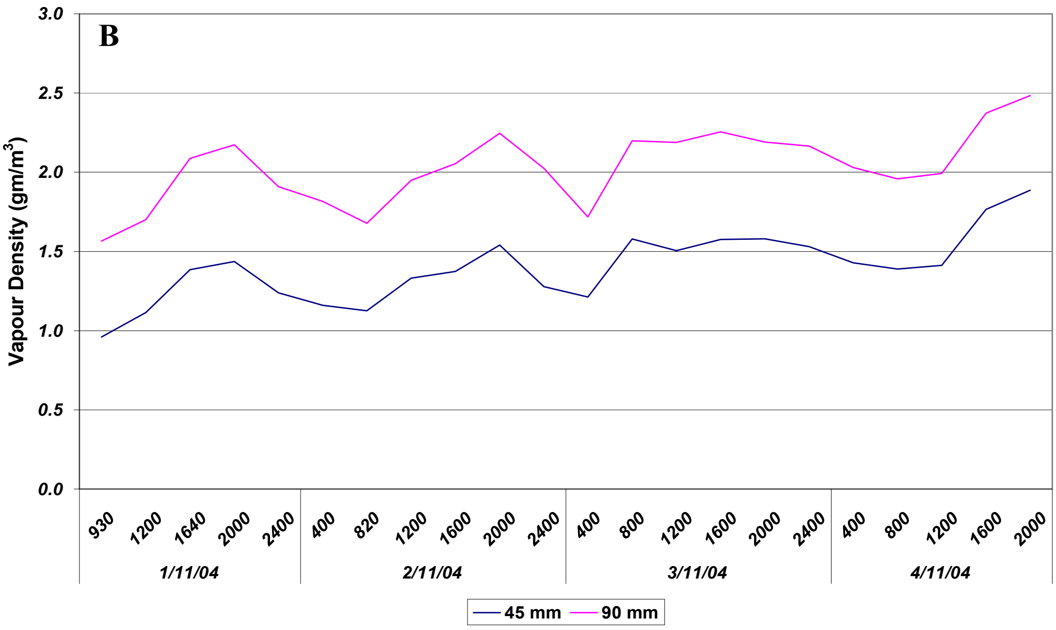


Figure 3.51: A. Teall Island west-facing site 45 mm and 90 mm vapour densities indicating the daily pattern and the lower amplitude and lag of the 90 mm moisture levels compared to the 45 mm ones, B. Terra Nova Bay south-facing site November 2004 indicating that depth measurements do not always cross

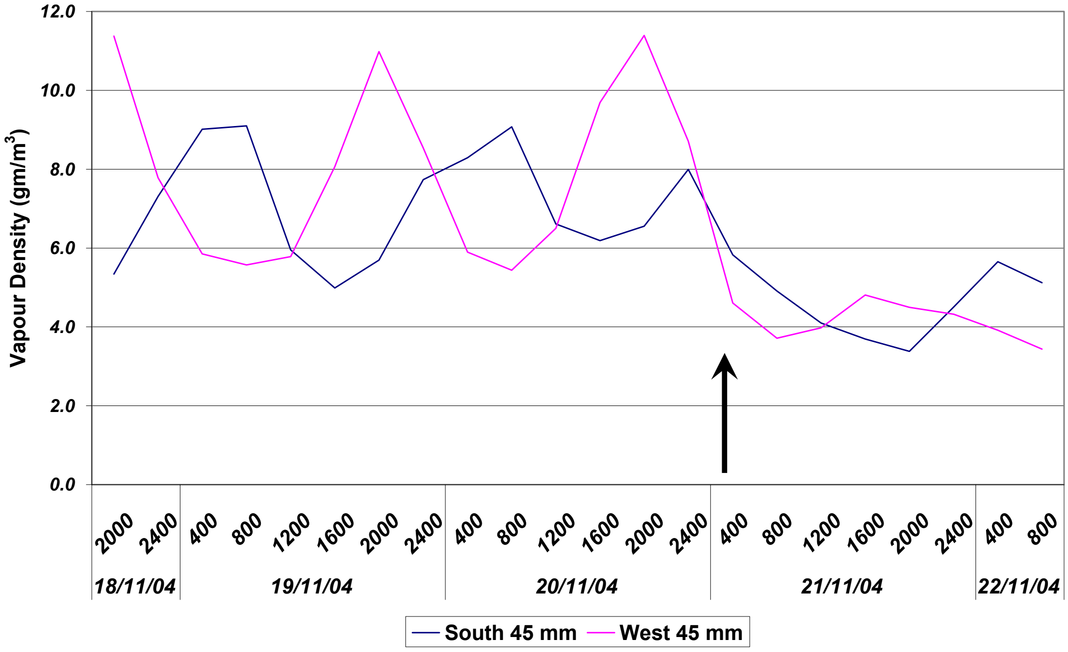


Figure 3.52: Teall Island south and west-facing site 45 mm vapour densities indicating the daily pattern and the appearance of wind and cirrus cloud on the 21st November 2004 (arrow)

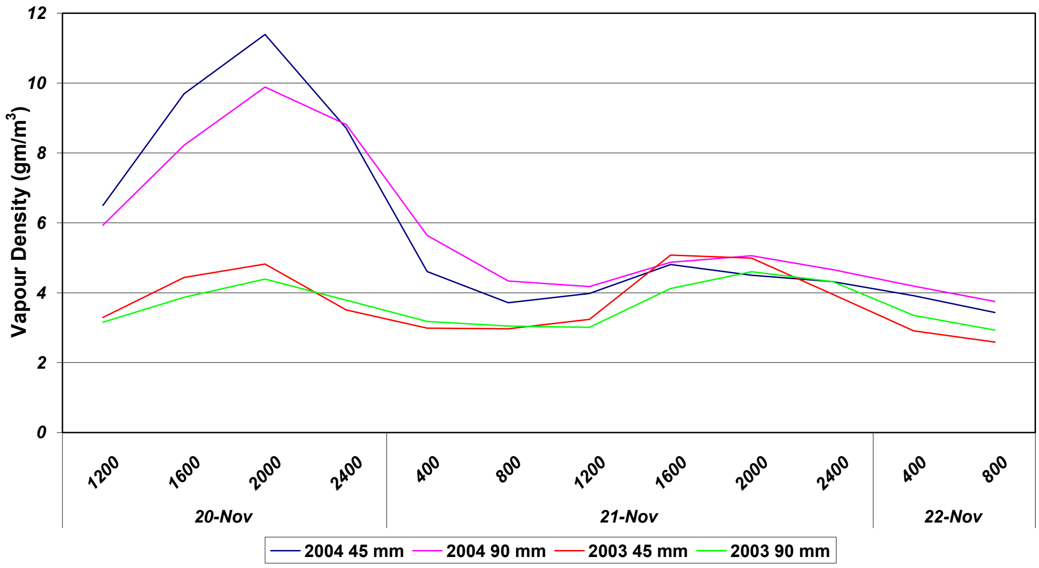


Figure 3.53: Comparison of the subsurface moisture regimes at the Teall Island west-facing site showing the differences between years

3.7 CLIMATIC VARIABLES

3.7.1 Methodology

Data on climate were collected at two scales: meso- and local. Meso-scale data were gathered from the nearest Automatic Weather Station (AWS). Table 3.4 summarises the location, source, types and frequency of data collected.

Table 3.4: Location of AWS and the frequency and type of data collected

Field Site	Nearest AWS	Approximate location in relation to field sites	Data collected	Freq-uency	Source
Terra Nova Bay	Eneide 74.70^{O}S 164.09^{O}E; 91.49m	1 km	Air temp; Wind speed & direction	hour	Programme Nationale di Richerche in Antartide
Gneiss Point	Marble Point 77.44^{O}S 163.75^{O}E; 108m	2 km	Air temp; Wind speed & direction	10 min	Antarctic Meteorological Research Centre (AMRC, USAP)
Victoria Valley	Lake Vida 77.38^{O}S 161.80^{O}E; 351m	0.5 km	Air temp; RH; Wind speed & direction; Soil temps; Solar radiation	15 min	McMurdo Long Term Ecological Research Project
Teall Island	Marilyn 79.95^{O}S 165.38^{O}E; 64.3m	120 km S 80 km E	Air temp; Air pressure; Wind speed & direction	10 min	AMRC (USAP)

As noted earlier data on air temperature, wind speed & direction, relative humidity and air pressure were collected at 4 hourly intervals during the times of actual site visits using a Kestrel 4000. The extent, height and type of cloud cover were also noted. Solar radiation was collected at each of the field locations at the same frequency as the rock surface temperature measurements. An attempt was made to collect data on precipitation during the 2002/03 season using an adapted Belfort rainfall gauge but this proved unsuccessful due to the small amount of actual precipitation and the fact that the specially prepared anti-freeze placed in the collection bucket froze!

3.7.2 Key Results

As noted elsewhere in the literature (e.g., Warke, 2000) air temperature was found to be a poor predictor of rock surface temperature, regardless of the proximity of the AWS. For example, at the Gneiss Point south-facing site the air was sometimes warmer than the rock surface and sometimes colder (Figure 3.54).

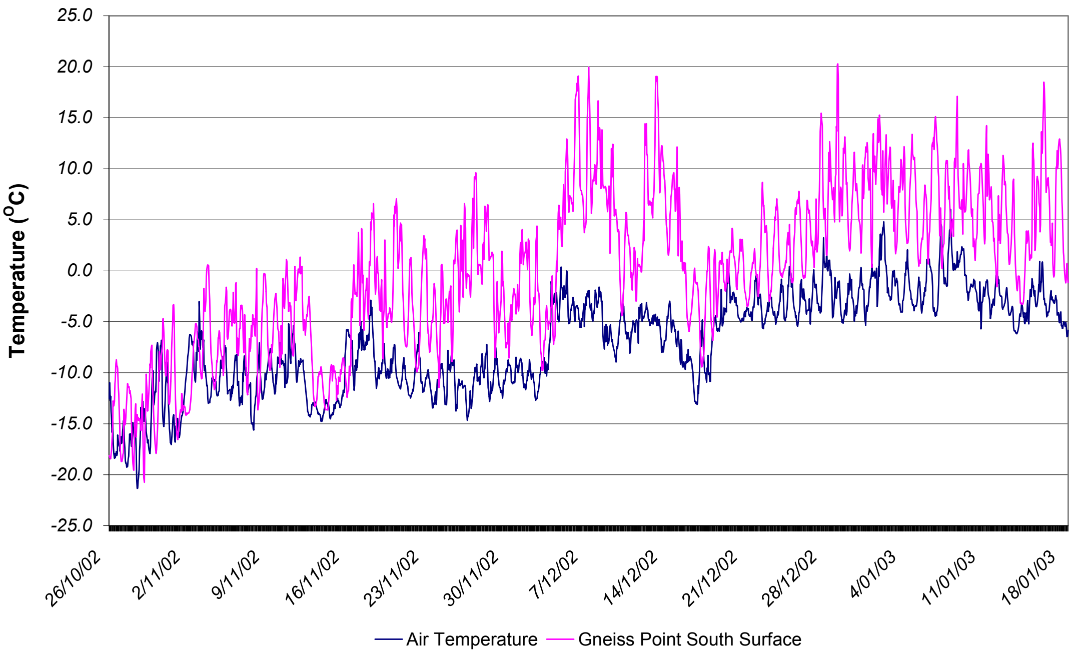


Figure 3.54: Air and Gneiss Point south-facing surface temperatures showing times when the air temperature is warmer than the rock surface and sometimes colder

Air temperature was found to fluctuate significantly even in the winter months, and again did not reflect surface temperatures (Figure 3.55). An analysis of these fluctuations together with wind patterns revealed that the air temperature was affected by both warm and cold winds coming off the ice cap (Figure 3.56).

Relative humidity was meant to be collected by most of the AWS but little data were actually recorded. Manual measurements taken with the Kestrel during site visits indicated that it generally ranged from 20 to 40% but fluctuated during the day and over time, reaching a low of 11.8% on one occasion and a high of 86.8% (during a snow storm) on another.

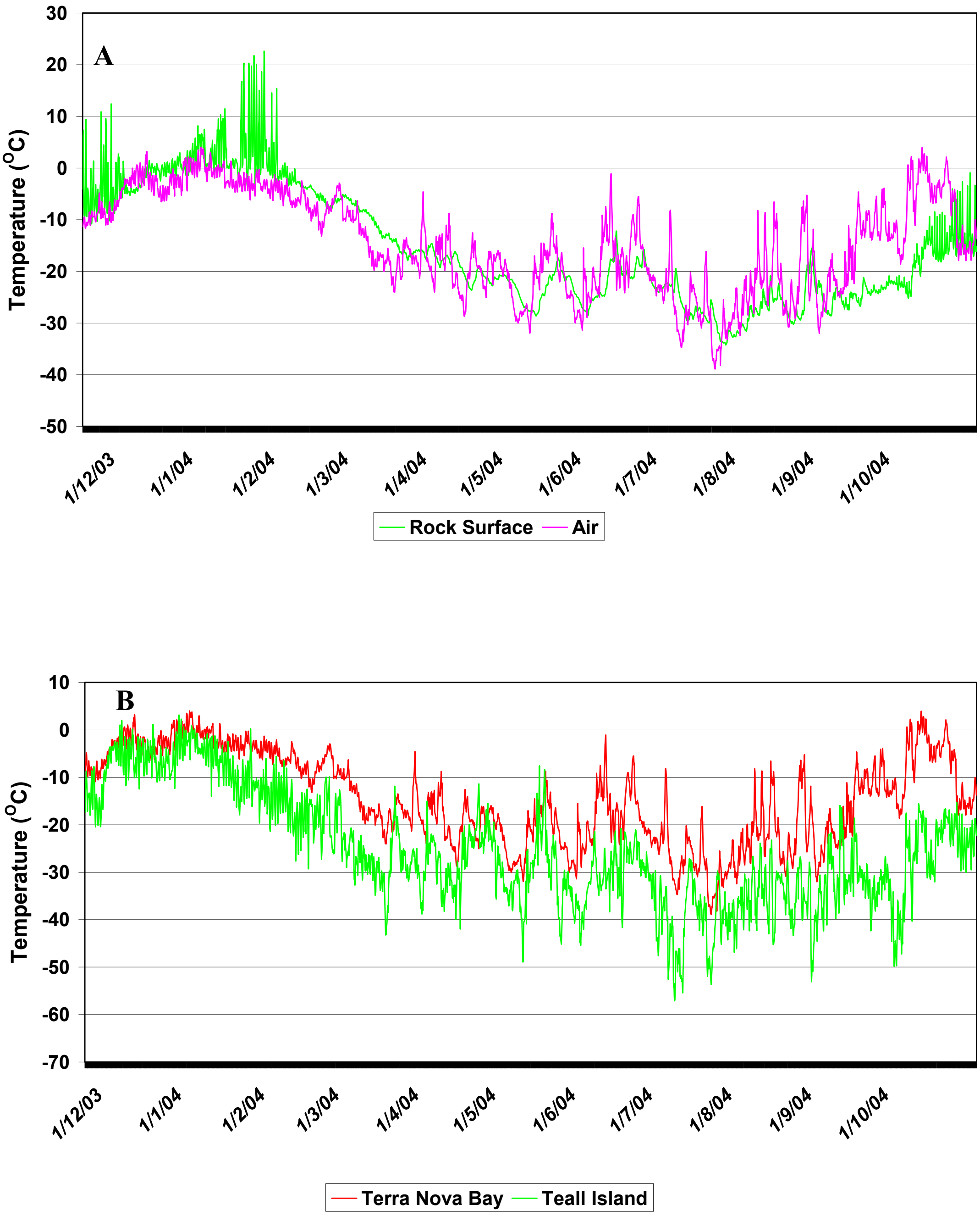


Figure 3.55: A. Air temperature recorded at Eneide AWS and the surface temperature at the Terra Nova Bay west-facing site showing the variable winter temperatures and B. Comparison of the Terra Nova Bay and Teall Island air temperatures between November 2003 and November 2004

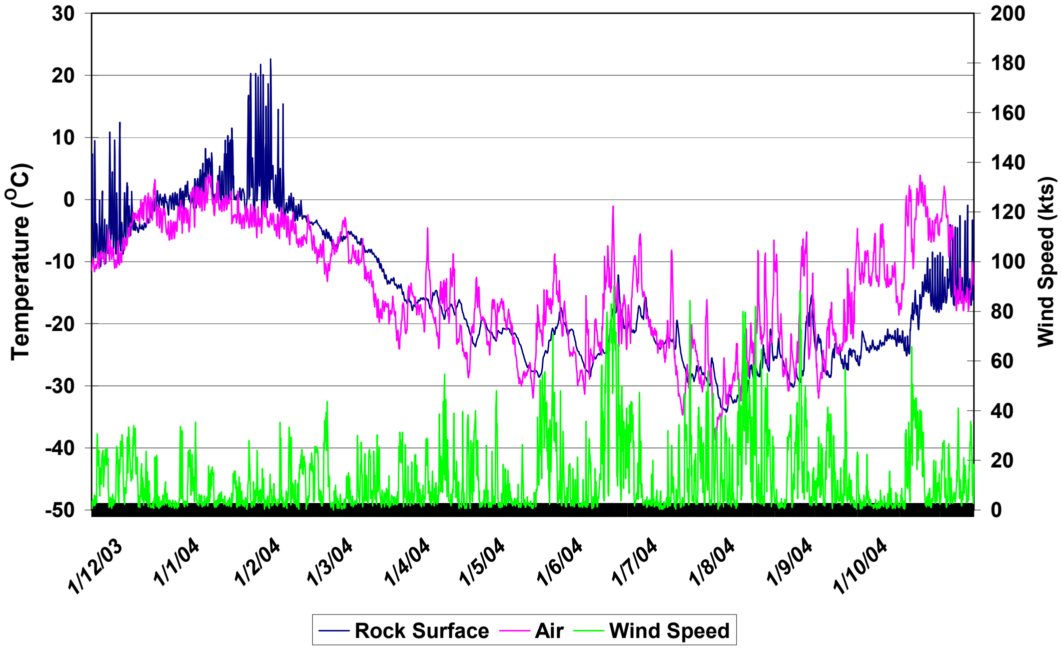


Figure 3.56: Air temperature recorded at Eneide AWS, the surface temperature at Terra Nova Bay west-facing site and the wind speed

Predominant wind directions as well as average summer and winter wind speeds are given in Table 3.5. These indicate that, with the exception of Victoria Valley, where the predominant wind direction is from the E-SE, all other locations are dominated by winds from a southerly direction. Average wind speeds increased in the winter and maximum speeds are significantly greater than the average in both summer and winter.

Table 3.5: Predominant wind directions and mean and maximum wind speeds by location and time of year

	Predominant Wind Direction (^{O})		**Mean (Maximum) Wind Speed (m/s)**	
	Summer	**Winter**	**Summer**	**Winter**
Terra Nova Bay	SW-W	SW-W	4.3 (22.6)	6.8 (50.4)
Gneiss Point	SE-S	N/K	2.7 (22.0)	N/A
Teall Island	S-SW	SW-W	2.8 (61.0)	6.7 (63.2)
Victoria Valley	E-SE	N/K	4.5 (15.1)	N/A

N/A – not available

3.8 SUMMARY AND RELEVANCE FOR THIS RESEARCH

Surface and subsurface rock temperatures as well as moisture were measured for two aspects at each of four locations over three seasons. Hourly averages were collected during the summer at all sites and three hourly averages for 12 months at Teall Island (both aspects) and Terra Nova Bay (west-facing aspect). In addition, one-minute measurements were made during summer at both aspects and all locations for a minimum of 48 hours. Issues with equipment meant that some of the data at Victoria Valley was either not collected or was not fully comparable with that from the other three locations. Apart from latitude, there were no apparent differences between the three coastal sites, although the Teall Island site was at a greater altitude (400 m) than either Terra Nova Bay (100 m) or Gneiss Point (50 m). These three sites were all within a few hundred metres of the sea but only Terra Nova Bay would experience open water for any length of time in each season. At most sites there was evidence of salt precipitation and biological activity as well as small quantities of running water following heating of the rock by solar radiation.

Absolute rock surface temperatures were affected by season and time of day. However, variability was influenced by local climate conditions such as wind, insolation, cloud cover and snow cover. Oscillations were progressively dampened with depth and there was evidence of a time lag to 90 mm depth. Rates of temperature change conducive to thermal shock were recorded at the surface only but the number of these varied with the precise location of the thermocouple, aspect and season. The number of freeze-thaw events depended on aspect and definition of a freeze-thaw cycle by a factor of two or more. Winter rock surface temperatures also varied, sometimes falling as low as -42 ^{O}C or rising to -10 ^{O}C and were dependent on air temperatures. Aspect and depth differences were only evident in the summer and spring/autumn seasons. A comparison of winter temperatures at Terra Nova Bay and Teall Island showed some correspondence indicating that macroclimate contributed to the winter variability. In addition, rock temperatures responded to changes in the winter air temperature following foehn and katabatic winds.

The presence of moisture on the surface of the rocks, primarily attributed to blowing snow, was more frequent than might be expected in this environment and occurred even in the presence of negative air temperatures. Rock surfaces could be wet up to 40% of the year but the frequency, duration, timing and quantity varied with location, aspect and time of year. Levels of subsurface moisture were measured at two depths over several days at each of the field sites for at least one season. Results indicated that subsurface moisture varied with time of day and depth. On occasions the 45 mm moisture levels were greater than those at 90 mm depth but at times they were lower. Differences in subsurface moisture between sites and aspects were also noted but they also varied with seasonal weather conditions, wind and cloud in particular.

There is no consensus about the most effective weathering process in this environment. However, there is recognition that a number of processes may operate depending on local environmental conditions. Table 3.6 builds on Table 2.5 by adding a column indicating the likelihood of each process or mechanism operating in this environment. This shows that frost weathering is unlikely to operate because of the high degree of saturation required (volumetric expansion) and the need for an ongoing moisture supply (capillary theory). However, Akagawa & Fukuda (1991) noted that high saturation was not required for ice lens growth. The most possible mechanisms in this environment are those of insolation weathering and wetting and drying (regardless of presence of clay). Salt weathering due to thermal expansion is also a possibility.

Table 3.6: Summary of the different physical weathering processes and mechanisms, requirements for their operation and likelihood that those requirements would be met in this research

Process and/or Mechanism	Requirements	Likelihood in this Research
Freeze/Thaw		
Hydraulic pressure hypothesis	High degree of surface saturation Rapid surface freezing	**Unlikely** to get the high degree of surface saturation required
Crystallisation pressure of ice	Permeable rock Ongoing supply of moisture	**Unlikely**: lack of ongoing supply of moisture
Volumetric expansion	High degree of saturation Rapid rates of freezing Crossing of 0 ^{O}C Closed system Long, thin cracks	**Unlikely** to get the high degree of saturation necessary
Capillary theory	Slow rates of freezing Porous rock Permeable rock $T \leq -5\ ^{O}C$? high saturation Open system of moisture Unidirectional freezing Cracks large compared to grain size	**Unlikely**: lack of ongoing supply of moisture
Insolation Weathering		
Thermal shock	Heating rate > 2 ^{O}C min^{-1}	**Possible**: evidence of these rates at the surface
Thermal stress fatigue	Repeated heating and cooling but range and frequency unknown	**Possible**: evidence of repeated heating and cooling both above and below zero
Wetting and drying		
Wetting and drying	Humidity fluctuations	**Possible:** humidity changes within rock demonstrated
Ordered water hypothesis	Humidity fluctuations Presence of clay	**Unlikely**: very low quantities of clay present in rock samples (Chapter 4)
Salt Weathering		
Crystallization from solution Hydration Thermal expansion	Presence of salt Decreasing temperatures to decrease solubility Temperature and humidity fluctuations	**Possible**: evidence of salt found at all locations but not able to determine type (Chapter 4) Temperatures and RH too low for hydration but thermal expansion possible

CHAPTER 4

ROCK DESCRIPTIONS AND CHARACTERISTICS

4.1 INTRODUCTION

The importance of the physical and chemical characteristics of the rock, including their mineralogy, was highlighted in Chapter 2.4. As noted earlier the influence of differing rock characteristics on the experimental results was minimised by choosing one rock group for the research. Granite Harbour Intrusives were selected partly because they are plentiful and relatively easily accessible along the Victoria Land Coast and partly because igneous rocks are the most common on the earth's surface (Strahler & Strahler, 1992). It was found that for an isotropic rock such as granite, the more porous it is and the larger and more angular its grains the lower its compressive strength. In addition, tensile strength decreases with increasing quartz content and is also affected by the presence of micro-cracks and their geometry. When considering the strength of granitic rocks porosity, grain size and shape as well as quartz content and the presence of micro-cracks are important.

Consequently, as well as general descriptions of the rock in the field, their physical (Section 4.2), chemical (Section 4.3), thermal (Section 4.4) and moisture (Section 4.5) characteristics were examined using a variety of laboratory and field tests. A table summarising all the characteristics of the rocks is provided in Section 4.6.

4.2 PHYSICAL CHARACTERISTICS

Thin section analysis revealed that the Gneiss Point rock was a homogeneous, equigranular, recrystallised, fine-grained granodiorite. Rare remnants of large plagioclase and alkali feldspar crystals were evident and there was minor sub-grain formation in the quartz as well as minor alteration of feldspar to muscovite. Figure 4.1 is a close up of the Gneiss Point south-facing rock surface which clearly indicates the mix of mineral types, including quantities of biotite, as well as their grain size and some iron staining is seen.

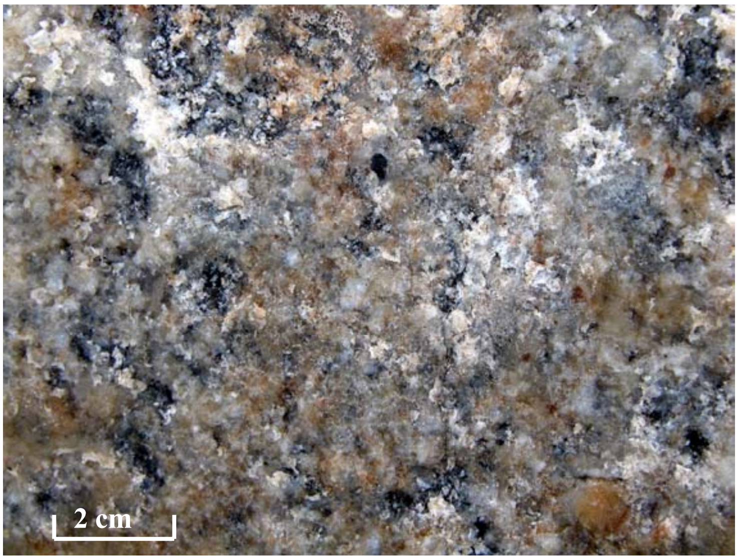


Figure 4.1: Close up of south-facing Gneiss Point rock surface

Photo-micrographs taken following thin section analysis found little evidence of micro-cracking (Figure 4.2A & B) and at least some of the cracks that did exist were filled (Figure 4.2B); there was also some evidence of annealing.

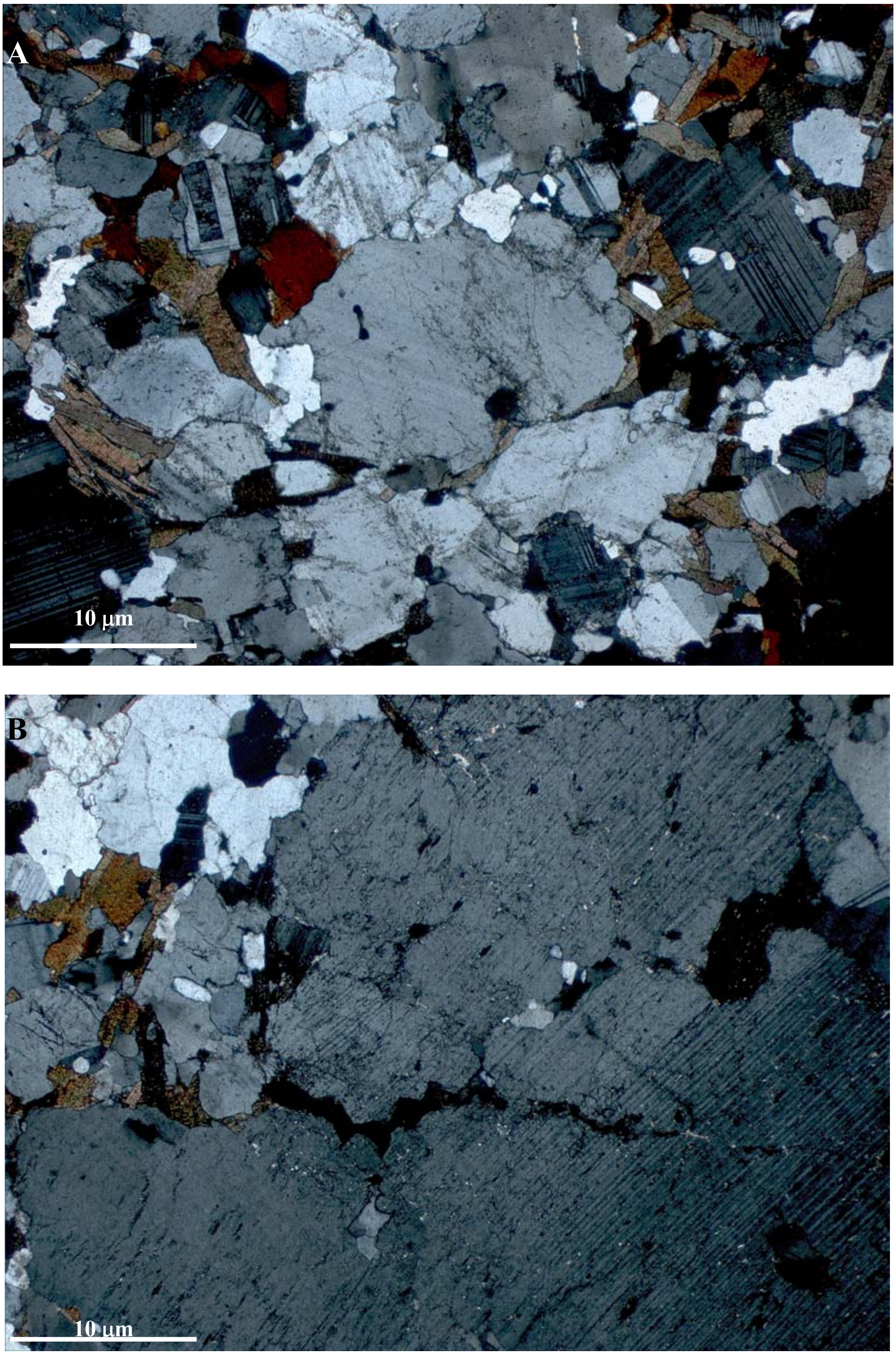


Figure 4.2: Photo-micrographs of Gneiss Point granodiorite. A. no evidence of micro-cracking B. a micro-crack approximately 20 μm long

The Victoria Valley rock was a coarse-grained, homogeneous granite. Quartz and plagioclase exhibited minor undulose extinction and annealing along mineral boundaries and plagioclase occurred rarely as euhedral phenocrysts. Oscillatory zoning was present in both varieties of feldspar and the biotite showed alteration to chlorite. There was extensive alteration of feldspar to sericite and minor muscovite, most likely deuteric or later hydrothermal alteration. The rocks were light grey in colour with large mixed crystals some of which were off white to cream and some of which were grey (Figure 4.3). Thin section analysis revealed that the rock was extensively micro-cracked (Figure 4.4A & B) and there was evidence of clay minerals in the cracks (Figure 4.4A).

Figure 4.3: Close up of Victoria Valley rock surface

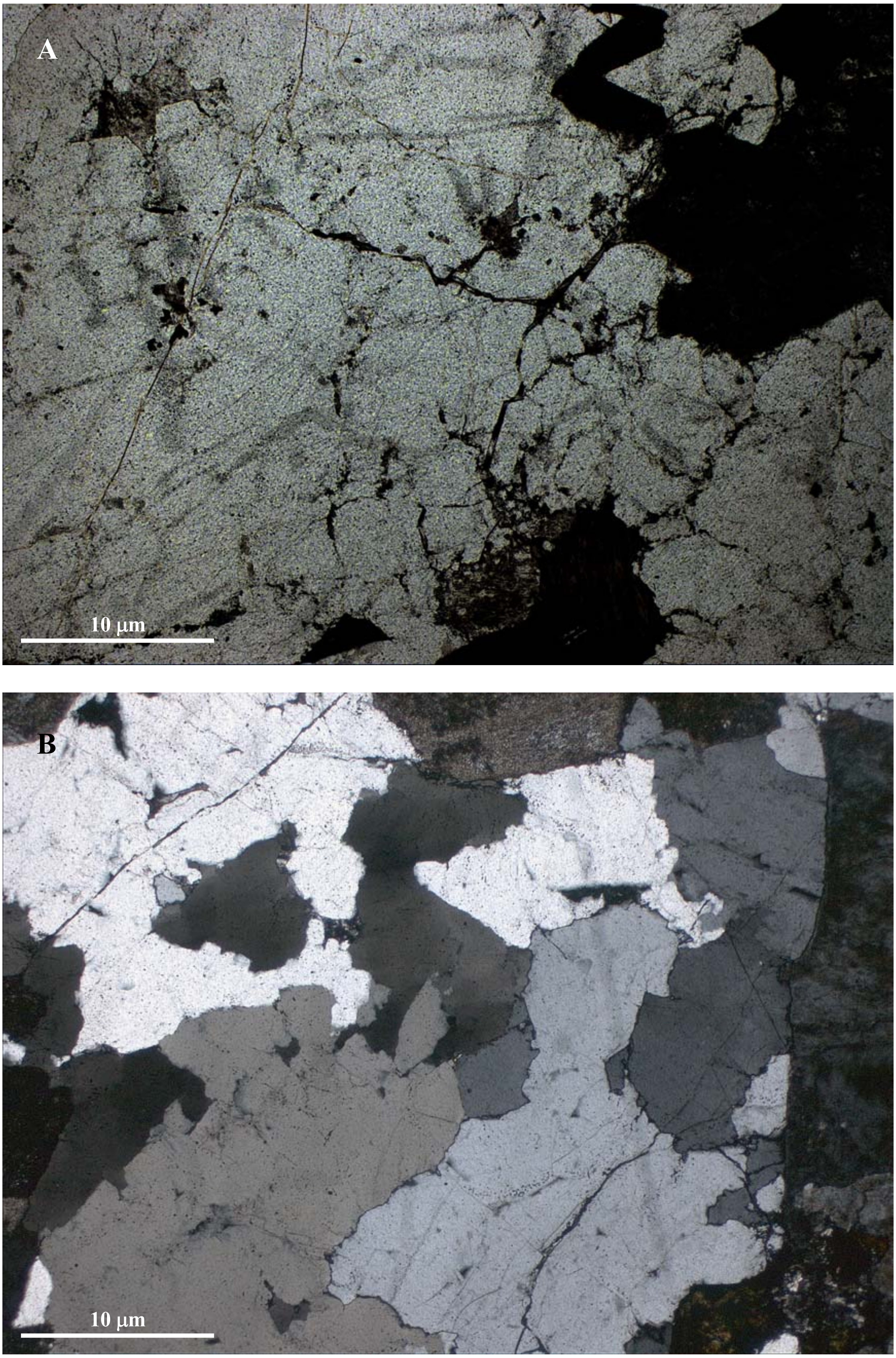


Figure 4.4: Photo-micrographs of Victoria Valley granite. A. Evidence of extensive micro-cracking and presence of clay minerals B. Extensive micro-cracking

The Terra Nova Bay granite contained large crystals of orthoclase feldspar (4 – 6 cm long), and glassy grey quartz crystals 2-3 mm long were scattered throughout the block. Biotite xenoliths, up to 17 cm long and 3 cm wide, were visible and crystals up to 0.5 cm maximum size were obvious. Some evidence of biological activity was evident just beneath the surface (Figure 4.5).

Thin section analysis determined that this was a porphyritic, medium-grained granite. Some larger quartz grains had undulose extinction and serrated boundaries and sub-grains were starting to develop and locally quartz was annealed. Plagioclase was present in the groundmass and as phenocrysts. Some crystals showed oscillatory zoning and myrmekitic texture is rare. Alkali feldspar was mainly microcline occurring as phenocrysts but was also present in the groundmass. Sericite and muscovite were common within the feldspar. XRD analysis suggested an alkaline granite but thin section analysis indicated the granite was fairly high in plagioclase. Sericite and muscovite resulting from pervasive alteration of feldspar, most likely deuteric or later hydrothermal alteration, were present. Photo-micrographs revealed cracking had occurred in all minerals (Figure 4.6).

Figure 4.5: Close up of Terra Nova Bay rock surface indicating size and mix of grains as well as evidence of biological activity

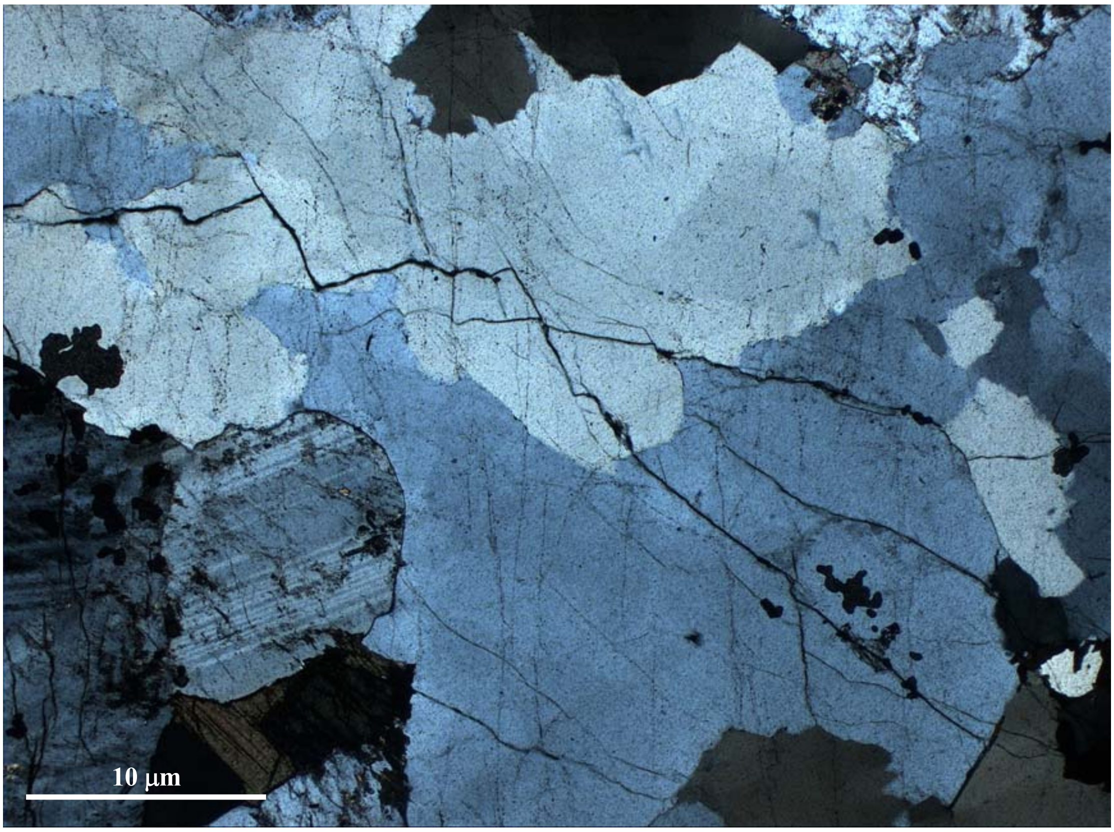


Figure 4.6: Thin section analysis of the Terra Nova Bay granite indicating extent of micro-cracking in all minerals

The Teall Island rock was a homogeneous, medium-grained granite (Figure 4.7). Microcline phenocrysts contained inclusions of biotite, quartz and feldspar and oscillatory zoning was apparent in some alkali feldspar phenocrysts. There was minor myrmekite development in the plagioclase feldspar and minor alteration of biotite to chlorite. Secondary muscovite was present in the centres of some feldspars.

Figure 4.7: Close up of rock surface at Teall Island

As for Terra Nova Bay, photo-micrographs indicated that there was extensive micro-cracking of all minerals (Figure 4.8).

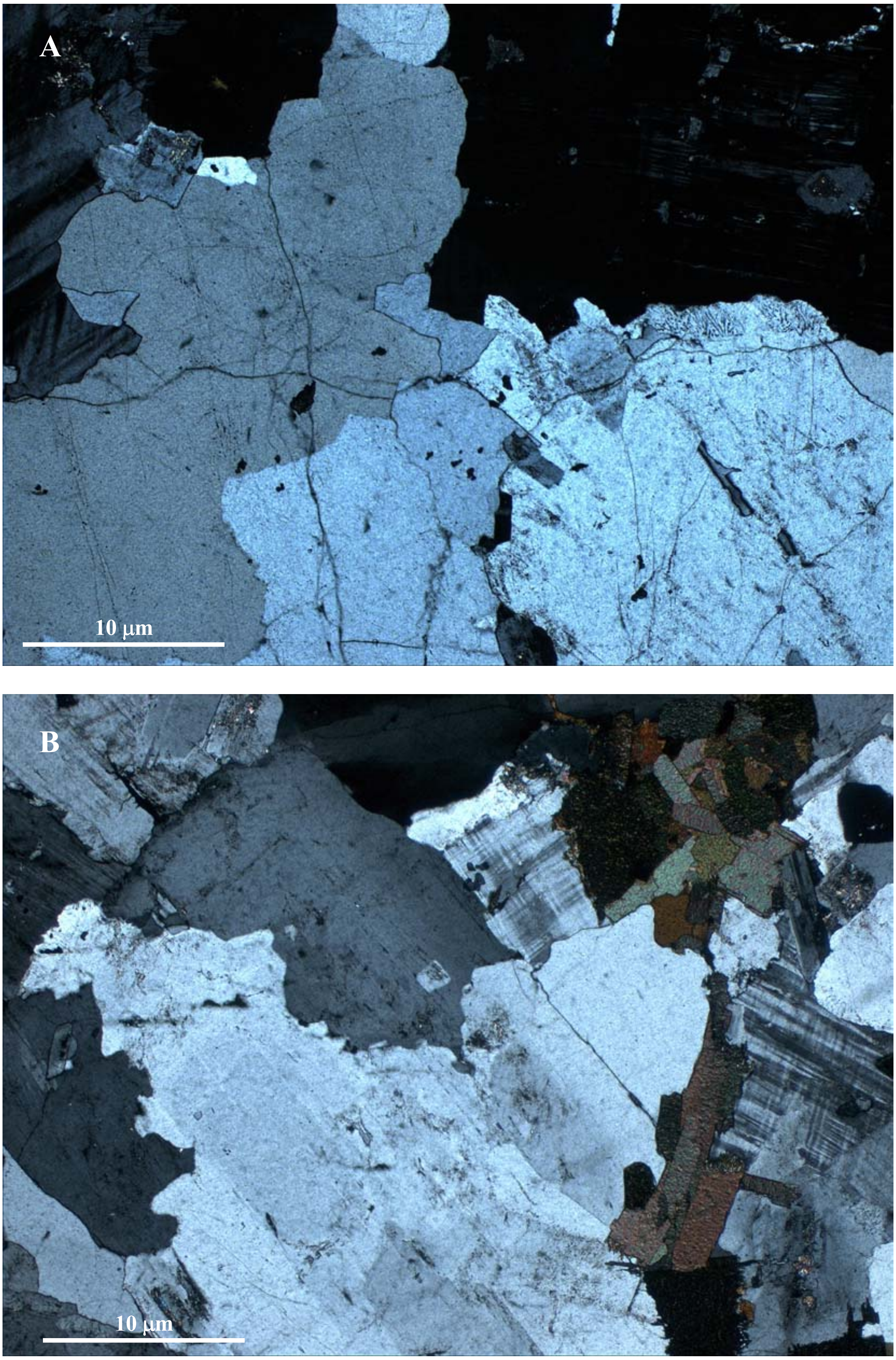


Figure 4.8 A & B: Photo-micrographs of Teall Island granite showing evidence of micro-cracking in all minerals

Thin section analysis was used to investigate micro-cracking as well as chemical and mineral composition (Section 4.3). However, there are some drawbacks to using this method such as the potential for the process itself to cause micro-cracks and that the area chosen may not be representative of the rock as a whole. In addition, thin sections by their very nature give no information on what happens at depth in the rock and these issues need to be born in mind in the discussions that follow.

Estimates of rock hardness, ultrasonic velocity and strength were undertaken in both the field and the laboratory (Table 4.1). According to Selby (1980) the Schmidt hammer measurements recorded in the field for this research indicated that the Gneiss Point south-facing rock was a very strong rock whereas the west-facing site was only moderately so, as were the rocks at both sites at Terra Nova Bay and Victoria Valley. The Teall Island rocks would be classified as weak rocks on the basis of their rebound values in Selby's (1980) classification.

Attempts to measure ultrasonic velocity in the field were only partially successful as it was sometimes either so cold that the connecting medium froze rapidly, or the rock surface was too rough for the size of paddle. Ultrasonic velocity was also measured in the laboratory using the samples prepared for the simulations. Differences in ultrasonic velocities between the longitudinal measurements and the transverse measurements indicated that there was some anisotropy in 60 to 80% of the 45 samples examined (15 each from Terra Nova Bay, Gneiss Point and Teall Island). There was evidence of some orientation of the crystals and possibly in the micro-cracks and it is likely that this affected these results.

Table 4.1 indicates the differences in the strength of the rocks depending on whether the measurements were conducted in the field or in the laboratory as well as the type of measurement. For example, according to ultrasonic velocity measured in the field the Teall Island south-facing granite was the strongest, but the Schmidt hammer measurements indicated this was almost the weakest. However, the effect of the cold temperatures on the connection medium for the sonic device may have affected these results. Point load strength was determined in the laboratory on small intact rock blocks that had been cut to size after being brought back from the field and they are consistently lower than the values quoted by Warke & Smith (1998 Table 1) for their granite. They are also generally lower than the range suggested by Attewell and Farmer (1976), shown in Table 2.2. Gneiss Point would be classified as a very strong rock, Teall Island as a strong rock and Terra Nova Bay and Gneiss Point as moderately strong rocks on the basis of their point load strength according to the classification by Selby (1980). However, all three measures are indirect measures of rock strength.

Table 4.1: Rock hardness, ultrasonic velocity and strength by location and aspect

		Rock Hardness[1] (R)		**Ultrasonic Velocity[3] (ms^{-1})**	**Point Load Strength (MPa)**
Gneiss Point	**S**	63		2282	8.8
	W	47		2798	
Terra Nova Bay		42		N/A	2.4
	W	40-43		N/A	
Teall Island	**S**	39		3264	5.5
	W	36		2347	
Victoria Valley	**N**	47		2073	3.0
	H[2]	42		1453	

[1] Median value used from first site visit and based on 40 to 50 replications; [2] Horizontal; [3] based on between 3 and 5 replications; N/A = not available

Effective porosity (percentage change in weight of a sample after saturation under vacuum) was also measured at the beginning of the laboratory experiment and Table 4.2 shows that whilst Terra Nova Bay and Victoria Valley had similar values Gneiss Point was by far the least porous with Teall Island moderately so, although all were very low. Measured values are within the range identified by Attewell & Farmer (1976) for granite (Table 2.2) but lower than the Mourne granite of Warke & Smith (1998).

Table 4.2: Effective porosity by location (mean of 15 replications)

	Gneiss Point	**Terra Nova Bay**	**Teall Island**	**Victoria Valley**
Effective porosity (%)	0.5	1.3	1.0	1.4

4.3 MINERAL AND CHEMICAL COMPOSITION

The mineral composition of the four rocks as determined by modal analysis is given in Table 4.3. These indicate that the quartz content of the Gneiss Point and Terra Nova Bay and the Teall Island and Victoria Valley rock are similar but the former pair had a higher proportion (36%) than the latter (29-30%). However, the feldspars and biotite exhibited the greatest differences in modal proportions. Teall Island and Victoria Valley had much lower plagioclase feldspars (2% and 10% respectively) than Gneiss

Point (39%) or Terra Nova Bay (26%) and correspondingly greater alkali feldspar contents. Teall Island and Victoria Valley were much richer in total feldspar than Gneiss Point or Terra Nova Bay but had lower biotite, with the latter two having similar quantities.

Table 4.3: Modal analysis of rock samples from the four field locations

	Gneiss Point	Terra Nova Bay	Teall Island	Victoria Valley
Quartz	36	36	29	30
Plagioclase feldspar	39	26	2	10
Alkali feldspar	11	20	60	56
Biotite	14	15	9	4
Horneblende	-	2	-	-
Trace quantities	muscovite (minor) titanite	muscovite (minor) apatite, zircon, epidote and opaques	chlorite (minor) muscovite and opaques	chlorite and apatite and rare epidote, zircon, titanite and opaques

These differences in modal proportions are reflected in the relative position of the four rock types in the Streckeisen (1976) classification of plutonic igneous rocks (Figure 4.9). The relative positions are based on point count data (300 points) following thin section analysis.

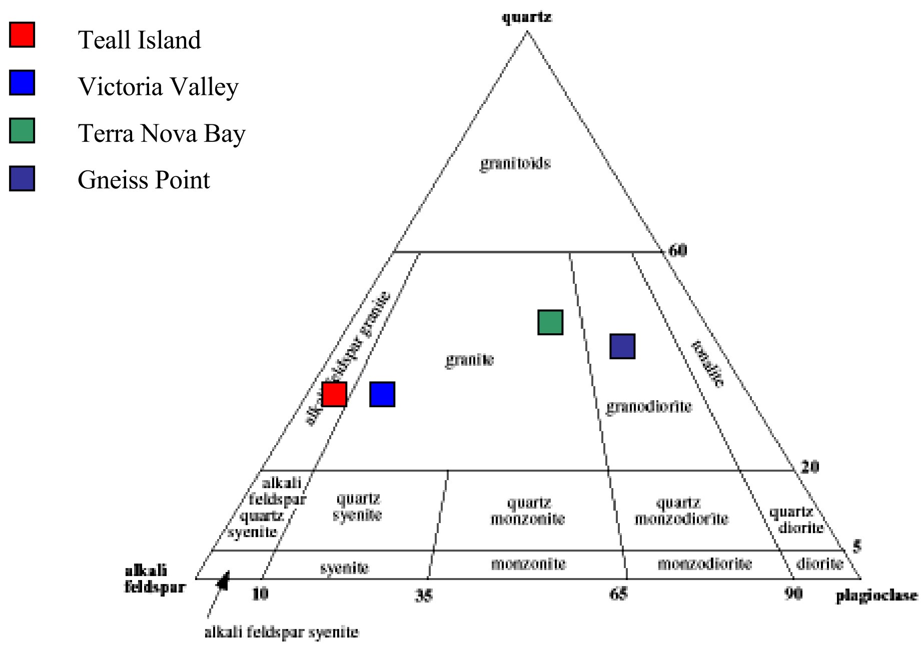


Figure 4.9: Classification using point count data of samples of rock from each location according to the Streckeisen (1976) classification

Table 4.4 gives the chemical composition of samples prepared from material taken from below the surface of each of the four rocks i.e., it was relatively fresh rock. This shows that Gneiss Point (68.15%) and Terra Nova Bay (69.5%) have lower silicon contents than the other rocks and that Gneiss Point also has the greatest proportion of aluminium, magnesium and calcium. On the other hand, Terra Nova Bay has more potassium and iron than the other two but less sodium. The variation in major elements between the samples is illustrated in Figure 4.10. A comparison with the average chemical composition of granodiorites and granites from Table 32 of Carmichel (1989) indicates that silicon levels are comparable but Al^2O^3, Fe^2O^3T and CaO are all higher in this study.

Table 4.4: Chemical composition of samples of rock from each location by XRF analysis

	Chemical Composition (%)										
	SiO_2	**TiO_2**	**Al_2O_3**	**Fe_2O_3T**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**SO_3**
Gneiss Point	68.15	0.42	17.85	1.90	0.02	0.74	4.42	5.04	1.42	0.11	<0.01
Terra Nova Bay	69.50	0.64	14.41	3.78	0.05	0.57	1.67	2.35	6.87	0.18	<0.01
Teall Island	71.89	0.23	15.02	2.30	0.07	0.48	2.11	4.36	3.23	0.07	<0.01
Victoria Valley	70.58	0.22	15.38	2.15	0.04	0.33	1.83	3.70	5.27	0.06	<0.01

4.4 THERMAL CHARACTERISTICS

Rock albedo was measured in the field using a pyranometer and Table 4.5 summarises the results for readings taken at 100 mm from the surface under sunny sky conditions. This again indicates a similarity between the Gneiss Point and Terra Nova Bay rocks and the Victoria Valley and Teall Island rocks with the latter having the greater albedo. These values are all much higher than those of the Northern Ireland granite used by McGreevy (1985) in his experiment.

Table 4.5: Albedo of rocks at 100 mm on a sunny day by location (mean of 10 replications)

	Gneiss Point	**Terra Nova Bay**	**Teall Island**	**Victoria Valley**
Albedo (%)	30	30	35	35

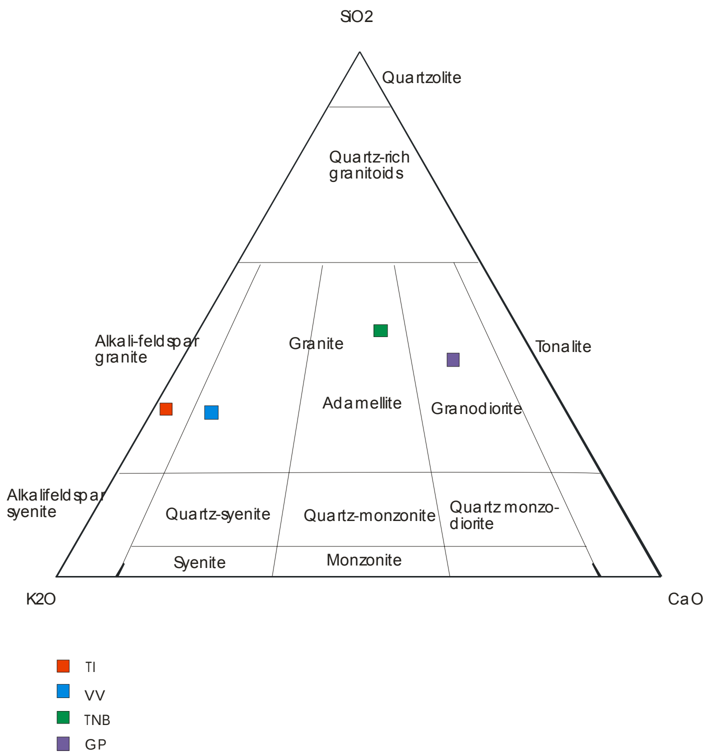


Figure 4.10: Streckeisen (1976) classification for plutonic igneous rocks after chemical analysis indicating composition of samples from each of the four field locations

Analysis of the surface and subsurface rock temperatures enabled estimates of thermal diffusivity, thermal conductivity and thermal admittance to be made (see Pringle et al., 2003 for method and algorithm used) (Table 4.6). It was not possible to estimate these for Victoria Valley due to problems drilling holes to the required depths. Pringle et al. (2003) used a graphical finite difference method to estimate thermal diffusivity. They ignored latent heat effects and heat flow other than by conduction and assumed that there were at least locally constant thermal properties. Heat Capacity was calculated using standard heat capacities for each element and thermal conductivity calculated from these. However, both thermal diffusivity and thermal conductivity are temperature dependent properties of a material (Clark, 1966) so that these values will change depending on temperature and hence season: thermal conductivity is higher at colder temperatures. In addition, latent heat effects cannot be ignored in the calculations undertaken here and so the values given in Table 4.6 should be seen as indicative only.

Anderson (1998) found values of between 1.6 and 1.8 mm^2 s^{-1} in his Wyoming granites and Warke (2000 citing Cermack & Rybach, 1982) quoted a range of between 1.3 and 4.5 W m^{-1} K^{-1} for thermal conductivity for granite. Generally the results calculated here are consistent with these, except for Gneiss Point and Teall Island south-facing sites. Certainly, the Teall Island south-facing figures look much too high.

Table 4.6: Thermal characteristics of the rocks at different depths, location and aspect

Location	Depth	Thermal Diffusivity (mm^2s^{-1})	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Thermal Admittance ($Jm^{-2}s^{-1/2}K^{-1}$)
Gneiss Point South	0	2.4	4.8	2.5
	45 mm	1.6	3.2	
	90 mm	1.0	2.0	
Gneiss Point West	0	1.7	3.4	2.1
	45 mm	1.1	2.2	
	90 mm	0.7	1.4	
Terra Nova Bay South	0	1.5	2.8	1.9
	45 mm	1.1	2.1	
	90 mm	0.9	1.7	
Terra Nova Bay West	0	2.1	4.0	2.3
	45 mm	1.4	2.6	
	90 mm	1.0	1.9	
Teall Island South	0	4.7	9.0	3.5
	45 mm	3.5	6.7	
	90 mm	2.9	5.6	
Teall Island West	0	1.5	2.9	2.0
	45 mm	1.1	2.1	
	90 mm	0.9	1.7	

4.5 MOISTURE CHARACTERISTICS

Two moisture characteristics of the rocks were measured: the rate at which it penetrated the rock under atmospheric pressure, a measure of sorptivity (Alexander et al., 1999 & Appendix 1) and the depth to which it penetrated, under a pressure of approximately 500 kPa, within a specific time period (European Standard 12390-8 & Appendix 1). Table 4.7 shows that the Teall Island rock absorbed moisture most rapidly whilst the Gneiss Point ones absorbed it the slowest. Interestingly these are also the two rock types most affected by the temperature at which the experiment was conducted.

Table 4.7: Moisture characteristics of the rocks

	Sorptivity ($g\ hr^{-1/2}$)		Penetration (mm)
	Warm	**Cold**	**Warm**
Gneiss Point	0.13	0.07	18.3
Terra Nova Bay	0.79	0.74	> 100
Teall Island	3.03	1.54	> 100
Victoria Valley	0.51	0.44	75.7

4.6 SUMMARY

Table 4.8 summarises the results from both the field and laboratory tests. This indicates that although the rock samples are all Granite Harbour Intrusives they have differing physical properties, particularly grain size, porosity, albedo and sorptivity. There are also differences in mineralogy: especially the proportions of quartz and feldspar as well as their chemical constituents. The characteristics of the rocks, as measured in the field, varied between locations. The Gneiss Point rock was a relatively fine-grained granodiorite whilst the Victoria Valley granite was coarse grained. Both the Terra Nova Bay and Teall Island granites consisted of medium sized crystals. There did not appear to be significant differences in particle shape between the rock types. According to the Schmidt hammer measurements and the Selby (1980) classification, the west-facing rocks at Gneiss Point and Terra Nova Bay were moderately strong whereas, for the same aspect at Teall Island, the rock was weak. The Victoria Valley horizontal site was also moderately strong. However, the point load strength tests on small intact blocks gives a different story, classifying Gneiss Point as very strong, Teall Island as strong but Terra Nova Bay and Victoria Valley as only moderately strong. Significant differences in the Victoria Valley Schmidt hammer readings over the course of the 2002/03 summer indicated that the very cold conditions in that season had affected the hammer itself, this has not been reported elsewhere in the literature.

It was not possible to measure ultrasonic velocity in the field at Terra Nova Bay because a good connection could not be made between the rock surface and the paddles. However, the Teall Island west-facing site had a lower velocity than the Gneiss Point west-facing site i.e. the Teall Island rock was weaker than the Gneiss Point rock, confirming the Schmidt hammer results, although it should be noted that the opposite was the case for the south-facing sites. Gneiss Point and Terra Nova Bay had the same albedo which was lower than that of Teall Island and Victoria Valley (which were the same). Terra Nova Bay had the highest surface thermal diffusivity and conductivity as well as thermal admittance and this was reflected in the depth calculations.

The strength of granite is affected by grain size, quartz content, porosity and extent of micro-cracking (Chapter 2) and an examination of these indicated that the Gneiss Point granodiorite was once again the strongest and hence the most resistant to weathering. Teall Island had a lower porosity and quartz content when compared to Terra Nova Bay making it the stronger of the two rocks but the picture for Victoria Valley was less clear with some characteristics such as porosity and quartz content enhancing its strength but others (i.e. micro-cracking and grain size) weakening it.

Table 4.8: Summary of rock characteristics

	Gneiss Point	Terra Nova Bay	Teall Island	Victoria Valley
Rock Type	Granodiorite	Granite	Granite	Granite
Physical Properties				
Grain size	fine	medium	medium	coarse
Effective porosity (%)	0.5	1.3	1.0	1.4
Field Strength (Schmidt, R)	47-63	40-43	36-39	42-47
Point Load Strength (MPa)	8.8	2.4	5.5	3.0
Albedo (%)	30	30	35	35
Density (Mg m^{-3})	2.629	2.547	2.555	2.541
Thermal conductivity[1] ($Wm^{-1}K^{-1}$)	3.4-4.8	2.8-4.0	2.9-9.0	N/K
Thermal diffusivity[2] (m^2 s^{-1})	0.0017-0.0024	0.0015-0.0021	0.0015-0.0047	N/K
Thermal admittance[2] ($Jm^{-2}s^{-1}K^{-1}$)	2.1-2.5	1.9-2.3	2.0-3.5	N/K
Specific heat capacity (J $kg^{-1}K^{-1}$ $x10^3$)	0.76	0.74	0.75	
Sorptivity[2] (g $hr^{-1/2}$)	0.13 (0.07)	0.79 (0.74)	3.03 (1.54)	0.51 (0.44)
Penetration (mm)	18.3	> 100	> 100	75.7
Mineralogy				
Quartz (%)	36	36	29	30
Plagioclase feldspar (%)	39	26	2	10
Alkali feldspar (%)	11	20	60	56
Biotite (%)	14	15	9	4
Other (%)		2		
Chemistry				
SiO_2 (%)	68.15	69.50	71.89	70.6
Na_2O (%)	5.04	2.35	4.36	3.70
K_2O (%)	1.42	6.87	3.23	5.27
CaO (%)	4.42	1.67	2.11	1.83

[1] depending on depth
[2] figures in brackets refer to cold temperature results

	Gneiss Point	Terra Nova Bay	Teall Island	Victoria Valley
Weathering/alteration	Minor sub-grain formation in quartz; minor alteration of feldspar to muscovite; few cracks and those that are are filled	Biotite unaltered; sericite and muscovite are common in feldspar; sericite and muscovite result from pervasive alteration of feldspar; extensive micro-cracking	Minor alteration of biotite to chlorite; 2^{O} muscovite present in centres of some feldspars; extensive micro-cracking	Biotite shows alteration to chlorite; extensive alteration of feldspars to sericite and minor muscovite

CHAPTER 5

LABORATORY SIMULATIONS OF WEATHERING RATES

5.1 INTRODUCTION

This chapter gives a brief outline of the purpose of the simulations, the rationale for the approach and the equipment used (Section 5.2). A description of a trial experiment conducted to test the methodology is given in Section 5.3. Section 5.4 provides details of the samples and sample preparation. The determination of the temperature cycles (Section 5.5); the method and frequency of moisture application (Section 5.6); the methods of determining the weathering rate at each location (Section 5.7) and for each process (Section 5.8) and finally, the statistical approach (Section 5.9) are also described. Details of the individual procedures necessary for each experiment (for example, measuring porosity) are included in Appendix 1.

5.2 EXPERIMENTAL SET UP

To achieve the research aims the following were required:

1. The total weathering rate for each of the field sites
2. Individual weathering rates for the specific processes under investigation: frost , heating and cooling, effect of humidity fluctuations
3. The effect of increasing moisture levels on weathering rates, and;
4. The relationship between weathering rates at the different locations

Goudie (2000) in his review of experimental physical weathering recommended that cycles used in simulations be based on field data. In addition, and due to the different specific heat and conductivity of rock materials to those of the air, Robinson and Williams (1994) stressed the importance of monitoring the rock rather than atmospheric conditions during simulated experiments. Consequently, the laboratory design was based on estimated rock temperature and moisture regimes that were as close as possible to those experienced in the field.

Several constraints had to be considered when designing the experiment:

- There were a limited number of rock samples
- These would be destroyed during the course of the experiment and so were not re-usable
- The time available for completion of the thesis

Therefore, it was important that the experimental design be as effective as possible. This was achieved by addressing several research questions concurrently and by increasing the frequency of temperature cycling. The latter technique has been used in a number of previous laboratory studies into rock weathering (e.g. Warke & Smith, 1998). In addition, an assumption was made that temperature cycling in winter would not significantly affect the results. A trial run was undertaken for several months and the outcome of this was used to modify the design of the final experiment (Section 5.3).

A commercial upright freezer, 2.0 m high, 0.8 m wide and 0.75m deep, was purchased and adapted to provide the environmental conditions required. It had a clear glass front door, a fan that circulated the air and 4 shelves (Figure 5.1). Holes were drilled (and subsequently sealed with rubber grommets) to enable 4 thermocouples and an intake for dry air to be inserted. Temperature cycling was driven by the topmost left hand thermocouple which was attached to the surface of one of the Gneiss Point samples (G05, see Section 5.4 for explanation of sample labelling). Two other thermocouples were attached to samples from Terra Nova Bay and Teall Island and the fourth one monitored the air temperature within the freezer. The thermocouples were connected to a Campbell 21X datalogger which had been programmed to switch the freezer on and off depending on the temperature of the rock surface of sample G05. The programme also recorded the actual as well as relative humidity within the freezer (Appendix 3). The programme was written to enable a tolerance to be entered on both the temperature and humidity levels and these were +/- 1 ^{O}C and +/- 0.5 gm/m^3 respectively. In addition, dry air was pumped into the freezer when the uppermost tolerance level for humidity was reached, although in practice this was rarely needed as the low temperature levels of the freezer maintained the necessary humidity levels.

Figure 5.1: Experimental set up showing the freezer

Samples were laid out in the freezer as shown in Figure 5.1. Sample positions were kept consistent throughout the experiment and monitoring of the temperatures did not indicate significant temperature differences between shelves.

5.3 TRIAL EXPERIMENT

A trial experiment was undertaken between May 2004 and February 2005. The purpose of this was to test the methodology and equipment and to:

1. Estimate the amount of weathering for a simulated 5 year period at each of the field locations

2. Estimate the amount of weathering over a 5 year period for one particular temperature regime and rock type, for each of the following processes

   (a) frost

(b) heating and cooling (thermal fatigue)

(c) wetting and drying

(d) salt weathering

3. Determine whether there were identifiable critical moisture levels for each process

The trial was begun prior to the collection of the data from Teall Island and was based on temperature cycles from the south-facing Gneiss Point site. Gneiss Point was chosen because it is approximately mid-way between the northernmost and southernmost coastal sites. The south-facing aspect had been selected for the trial because it provided the most clearly distinguishable cycles (at least on the data available at that time). The intent had been to subsequently repeat the experiment using data from the other locations.

The weathering year was defined as extending from the beginning of November until the middle of March each year (20 weeks). This was based on the assumption that, because there was little or no sun to drive the temperature or moisture changes within the rock, little if any weathering took place during the Antarctic winter. In fact, when the twelve month data from Terra Nova Bay (west-facing) and Teall Island (west- and south-facing) sites had been collected this indicated that significant temperature cycling did occur during the winter period (Section 3.4).

A number of different approaches to the method of applying, as well as determining the quantities, of moisture to be applied were considered. These included estimating the moisture at the 45 mm depth and applying those levels either by using a drip or spray method. However, the levels involved were so small that it was not possible to find equipment that was sufficiently sensitive to undertake the job. In addition, application by drip in sufficient levels to be measurable would not be absorbed by the low porosity rocks under consideration here (Section 4.2). An automated spray within the freezer was also considered but again it was not possible to design this to spray the quantities required or to prevent the moisture freezing before it could be applied during the below zero cycles. Consequently, moisture was applied by considering the porosity of the least porous of the rocks (Gneiss Point: 0.5%) and using levels of saturation under atmospheric pressure. A small controlled experiment was undertaken to estimate potential soaking times that would approximate various proportions of saturation. In the trial experiment 3 levels were used for the overall weathering rate (0; 25%; 50%) and 5 levels for the individual process rates (0; 25%; 50%; 75%; 100%). Moisture was applied only once at the beginning of each set of temperature cycles.

Unfortunately few significant results were found from the trial run, either because of insufficient length of simulated time or inadequate or unrealistic moisture applications. The experiment was subsequently redesigned and simplified to exclude one of the sites (Victoria Valley) and the salt weathering investigations. Other changes are discussed within the relevant sections.

5.4 SAMPLES AND SAMPLE PREPARATION

Two different types of sample were used: small pre cut rock blocks and specially prepared aggregates. The pre-cut blocks were used to simulate weathering from rock outcrops or large boulders whereas the aggregates were used to simulate weathering of grus, which was evident at all the field sites (for example Figure 3.9). Samples collected in the field were examined visually for soundness before being selected but those that showed significant internal weathering or cracking during sample preparation were subsequently discarded. Blocks measuring 10 cm x 5 cm x 5 cm were cut from the inside of the field samples using a circular rock saw. They were then wiped clean, measured, photographed and labelled according to the following system (Table 5.1). For example, G05 was the fifth replicate of the Gneiss Point samples that had no additional moisture applied.

Table 5.1: Labelling system used for the samples

Location Identifier	Moisture Level	Replicate Number
G = Gneiss Point t = Terra Nova Bay T = Teall Island	0 = no additional moisture applied 1 = half saturation 2 = full saturation	Allocated numbers from 1 to 5

Initial porosity was determined and the ultrasonic wave velocity measured in two directions (Appendix 1). Aggregates were prepared in line with the methods of Fahey (1983). Rock blocks were crushed (using a commercial rock crusher) and sieved to remove any particles greater than 16 mm (-4.0 Φ) or less than 2 mm (-1.0 Φ) in diameter. Individual samples of approximately 200 gm in weight were then prepared and sieved to determine the particle size distribution. Quarter phi intervals were used for particles between – 1.0 Φ and – 2.0 Φ and half phi intervals for the larger ones (-2.5 Φ to -4.0 Φ).

Practical considerations helped to determine the number of replicates. From a statistical point of view the greater the number of replicates the better. However, only so many rock samples could be brought back from Antarctica and only so many would fit in the freezer. Balancing all factors out it was decided to use 5 replicates for the small rock blocks and three for the aggregates.

5.5 Determining the Temperature Cycles

In the revised experiment the rock surface temperatures for the west-facing coastal sites were averaged. The west-facing site was chosen as this was the aspect for which 12 month data were available at two sites as well as being the aspect that was likely to produce the most weathering (since it faced inland towards the ice cap). The west-facing rock surface temperature data from November 2003 to November 2004 are shown in Figure 5.2.

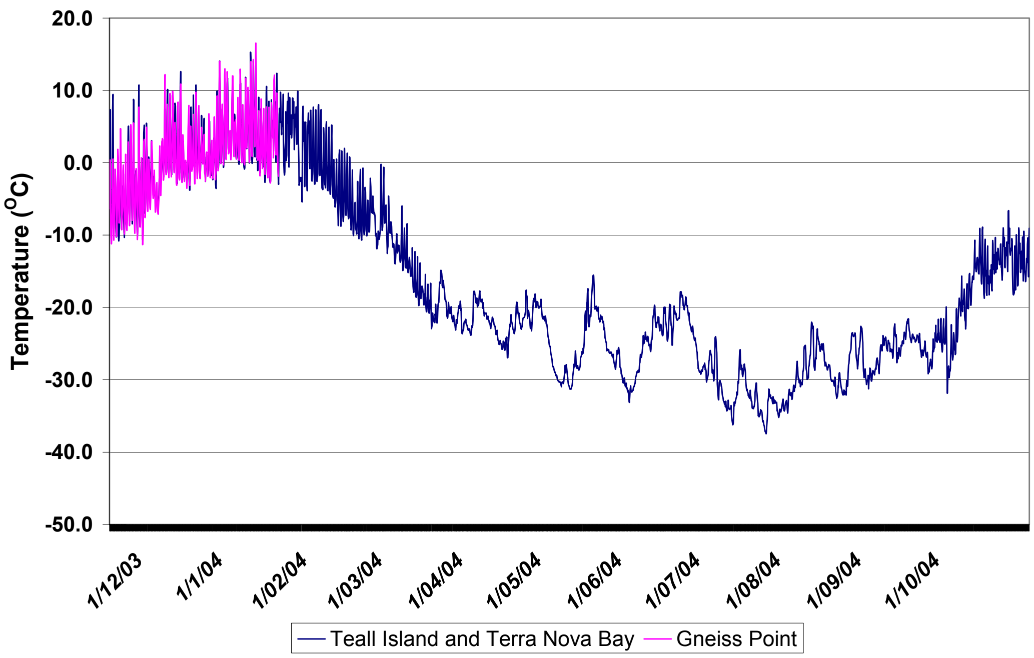


Figure 5.2: Rock surface temperatures from 14 November 2003 to 30 October 2004 showing the average for Teall Island and Terra Nova Bay west-facing sites as well as the effect of including the summer temperatures from Gneiss Point.

An analysis of the average 75th and 25th percentile values of the rock surface temperatures for the summer, spring/autumn and winter periods identified the three temperature cycles to be used for the simulations (Table 5.2). The 75th and 25th percentiles were chosen as these are used when describing distributions that might be unduly affected by extreme values (Yeomans, 1968). Summer was defined as being from the beginning of December until the end of January, spring from the 1st of November until the end of November, autumn from the beginning to the end of February and winter from the 1st of March until the end of October. The Gneiss Point data had little influence on the averages so that it was effectively the mean of the rock temperatures from the northernmost (Terra Nova Bay) and southernmost (Teall Island) locations that were used (Figure 5.2).

Table 5.2: Temperature cycles used in the simulations

Period	**No. of Days in Period**	**Temperature Cycle (^{O}C)**
Summer (1/12 to 31/1)	62	+ 6 to 0
Spring/Autumn (1/11 to 30/11 & 1/2 to 28/2)	58	+ 2 to - 6
Winter (1/3 to 31/10)	245	- 20 to – 30

The temperature cycles enabled the effects of above zero, across zero and below zero cycling to be investigated. In addition, the across zero cycle was consistent with the definition of an 'effective' freeze-thaw cycle: a fluctuation from less than –2 ^{O}C to above +2 ^{O}C and back below –2 ^{O}C within a 24 hour period (Matsuoka, 1990b). The winter temperature cycling was the subject of future research.

The number of temperature cycles to be undertaken during each real day (i.e. how much to accelerate time) was determined by comparison with previous experimental work and practical considerations. Six cycles per 24 hours provided a timescale that was feasible within the time available and gave temperature gradients that were consistent with other studies. For example, Lautridou and Seppala (1986) used a rate of freezing of 3-4 ^{O}C hr^{-1} until temperatures reached – 5 ^{O}C and then 1.5 ^{O}C hr^{-1}, thereafter whereas Hall (1988) used a variety of rates of change from 1 ^{O}C hr^{-1} to 6 ^{O}C hr^{-1}. A summary of the rates of temperature change is given in Table 5.3.

Table 5.3: Rates of change of temperature used in the experimental work

Period	Rates of Change of Temperature ($^{O}C\ hr^{-1}$)	Number of Completed Cycles
Summer	3	371
Spring/Autumn	4	354
Winter	5	Future Research

5.6 APPLIED MOISTURE LEVELS

Three moisture levels were used for the overall weathering as well as individual process rates: 0%; 50% and 100% saturation. These are slightly different to those described in Section 5.3 and were chosen in order to simplify the experiment and reduce the number of samples required. Samples were immersed in water for 0, 7 minutes, and 1 hour in line with the results of a controlled experiment that had shown that the relationship between time and water take up was not linear. Moisture was applied every 3 to 4 days under atmospheric pressure to model behaviour in the real world. In total 16 moisture applications were undertaken for the summer, and 14 for the spring/autumn experiments. The same approach was used for the aggregates.

5.7 METHOD OF DETERMINING WEATHERING RATES AT EACH LOCATION

The samples and aggregates from each location were subjected to a simulated 5 years of weathering using the estimated temperature cycles and moisture levels. For the rock blocks weathering rate was estimated by measuring changes in the weight of the samples (e.g. Hall & Hall, 1996), as well as their strength (e.g. Fahey & Gowan, 1979). Two measures were used to estimate the latter: ultrasonic wave velocity and effective porosity. Ultrasonic wave velocity was measured using the portable ultrasonic device used in the field. In order to ensure that measurements were comparing like with like all samples were dried to constant weight at 60 ^{O}C at the end of each set of temperature cycles. The average change in weight, effective porosity and the average change in ultrasonic velocity (in each of two perpendicular directions) were calculated for the replicates and these values used as the final estimates for the statistical analysis. The potential effect of differences between the rock samples was measured by subjecting samples from all three locations to the same set of experiments. The rock blocks were also photographed at the beginning and end of the experiment.

The effect of weathering on the aggregates was determined by comparing changes in the particle size distribution between the beginning and end of each set of temperature cycles as well as in the proportion of material less than 2 mm in diameter. The effect of the sieving itself on the aggregates was measured by subjecting three samples to five sievings each. This determined that on average weight loss was 0.003% (0.52 g) per sieving.

5.8 METHOD OF DETERMINING PROCESS RATES

The experimental set up enabled three different processes to be investigated: frost, thermal fatigue and the effects of fluctuations in humidity under different temperature cycles. Weathering rates were estimated using the same measures as described for the overall weathering rates (Section 5.7).

5.8.1 Frost

Measurement of the effect of freezing and thawing on weathering rate was identified as the contribution to the overall weathering rate (using the measures described above) from the across zero temperature cycles. The three saturation levels enabled a moisture effect (within this temperature cycle) to be determined and the statistical approach ensured that the contribution of any temperature cycle or moisture x cycle interaction were identified (Section 5.9). Rock blocks and the aggregates were subjected to this regime.

5.8.2 Heating and Cooling (thermal fatigue)

Two of the temperature cycles used in the weathering rate simulations provided the necessary repetition for this process: the above freezing cycle of 0 ^{O}C to + 6 ^{O}C and the winter or below zero cycling of – 20 ^{O}C to – 30 ^{O}C. This process does not require the rapid temperature gradient of thermal shock or the necessity of crossing the zero degree isotherm as in freeze-thaw but is deemed to be a response to the temperature cycles only. The samples and aggregates were subjected to the 3 different moisture levels identified in Section 5.6 The dry regime (zero moisture) tested the effect of thermal fatigue alone (although there were humidity fluctuations), whilst the 50% and 100% saturation levels tested the additional effect of moisture. The statistical approach enabled the effect of temperature cycle, moisture level and any interaction between the two to be determined (Section 5.9).

5.8.3 Humidity Fluctuations

One set of samples from each location did not receive any additional moisture and the results from these experiments provided information on the effects of humidity variations alone in conjunction with above and below zero temperature cycling.

5.9 STATISTICAL APPROACH

Five replicates of the rock blocks were used in the experiment. However, because weight loss and effective porosity can be greatly influenced by the particular micro-characteristics of the individual samples within group variability was examined using a series of box plots (McClave & Sincich, 2000). These identified both 'outliers'[3] and 'extremes'[4] and the extremes were excluded from both analyses to prevent the results from becoming overly influenced by these values. One-sided paired sample t-tests were then conducted to compare weight loss between the initial weights and those after each set of temperature cycles. The same approach was undertaken for effective porosity but, because this could either increase or decrease during the experiment, a two-sided test was used. Analysis of variance was undertaken when comparing means between moisture levels for the three temperature cycles.

Repeated measures analysis was used to investigate any significant moisture-cycle interaction or main moisture or cycle effects (i.e. the effect of moisture over all cycles or the effect of cycles over all moisture levels). This technique has been used in ecological studies and applies to situations where there are a number of population groups each of which is measured over either different time intervals or sets of treatments (von Ende, 1993). In this case the three moisture levels are the population groups and the temperature cycles are the second set of treatments, which are considered as dependent variables.

This approach enabled the following to be determined:

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[3] Defined as cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box, where the box length is the inter-quartile range

1. Moisture level x temperature cycle interactions
2. The effect of the moisture levels on weathering rate (i.e. over all temperature cycles)
3. The effect of the temperature cycles on weathering rate (i.e. over all moisture levels)

5.10 SUMMARY

An adapted upright freezer was used to simulate the climatic conditions as closely as possible to those of the environment under consideration, in line with recommended practice (Goudie, 2000; Robinson & Williams, 1994). Rock surface temperatures were used to drive the temperature cycling and were monitored throughout the course of the experiment. The maxima and minima for the cycles were determined by calculating the average 75th and 25th quartile values. Pre-cut rock blocks and specially prepared aggregates were subjected to the same temperature and moisture conditions. A trial run enabled changes to be made to the experiment.

Time was accelerated in line with previous research (e.g. Hall, 1988b; Lautridou & Seppala, 1986; Warke & Smith, 1998). Three levels of moisture were investigated and changes in weight, effective porosity and ultrasonic velocity were measured at the beginning and end of each set of temperature cycles and moisture was applied to the appropriate replicates every 3 or 4 days.

This approach enabled the potential effects of freezing and thawing, heating and cooling (thermal fatigue) and wetting and drying in conjunction with temperature change to be investigated. The statistical analysis enabled moisture effects, cycle effects and any interactions to be determined.

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[4] Defined as cases with values more than 3 box lengths from the upper or lower edge of the box, where the box length is the inter-quartile range

CHAPTER 6

RESULTS OF LABORATORY SIMULATIONS

6.1 INTRODUCTION

A comment on the temperature cycles used in the simulations is given in Section 6.2 and the results of the individual temperature cycles are detailed in Sections 6.3 (above zero cycling), 6.4 (across zero cycling) and 6.5 (below zero cycling). The cumulative effects of all cycling are described in Section 6.6. A summary of the main results is given in Section 6.7.1 and an interpretation of these results, including a discussion on how they relate to earlier work as well as the specific research questions for this study is contained in Section 6.7.2. Implications for cold climate weathering generally are outlined in Section 6.8.

6.2 TEMPERATURE CYCLES

The particular temperature regimes identified by the fieldwork gave an opportunity for the effects of above zero, across zero and below zero cycling to be investigated for three moisture levels: no moisture, half saturation and full saturation and for all three rock types falling within the Granite Harbour Intrusive group. Temperature cycling was determined using the 75th and 25th quartiles of the average of the hourly rock surface temperatures for the three coastal sites and the freezer was controlled by the cycling of one of the no moisture Gneiss Point samples (Sections 5.2, 5.5). However, the actual cycles experienced by the samples from each location differed so that whilst the Gneiss Point samples cycled above zero (+ 5.5 to +1.5 ^{O}C), both Terra Nova Bay and Teall Island cycled across zero (+1.5 to -3 ^{O}C and +2 to -2.5 ^{O}C respectively). The Terra Nova Bay (-4 to -10 ^{O}C) and Teall Island (-3.5 to -9 ^{O}C) samples experienced cycling below zero when Gneiss Point was cycling across zero (+1.5 to -4.5 ^{O}C) (Table 6.1). This meant that in practice, only the Gneiss Point samples experienced above zero temperature cycling; all three experienced across zero temperature and Terra Nova Bay and Teall Island cycled below zero. The reason for the differences in response by the rock blocks to the same ambient freezer temperature is inferred to be due to the individual properties of the rocks.

The temperature of the freezer, which can be regarded as ambient air temperature is also given in Table 6.1. These two cycles could be regarded as summer air temperatures (+5 to -1.5 ^{O}C) and spring/autumn temperatures (+1 to -8 ^{O}C). The implications of these are discussed in Section 6.8 and Chapter 7 in particular.

Table 6.1: Intended and actual temperature cycles experienced by the different rock samples

Intended Cycling	**Actual Cycling* (^{O}C)**			
	Terra Nova Bay	**Gneiss Point**	**Teall Island**	**Freezer (Air)**
+6 to 0 ^{O}C	+1.5 to -3	+5.5 to +1.5	+2 to -2.5	+5 to -1.5
+2 to -6 ^{O}C	-4 to -10	+1.5 to -4.5	-3.5 to -9	+1 to -8

* to nearest half a degree centigrade

The temperature of the aggregates was not monitored during the experiment and so it was not known whether the samples from the three locations responded differently to the freezer temperature but it was assumed that they did not due to the size of the materials.

6.3 Above Zero Temperature Cycles

6.3.1 Rock Blocks

Statistically significant weight loss occurred for all moisture levels in the Gneiss Point samples for the above zero temperature cycles. Proportionally, (total weight loss of all replicates expressed as a proportion of total initial weight), the greatest loss was experienced by the half saturated samples but this was not significantly different to the other moisture levels (Table 6.2). The variability of individual sample results fro each moisture level is given in Figure 6.1. This indicates that variability has increased with moisture level but that there are no extreme values.

The fully saturated samples also experienced a significant decrease in effective porosity and a significant increase in ultrasonic velocity (Table 6.3). Repeated measures analysis indicated a significant moisture effect for effective porosity between the fully saturated samples and the other moisture levels for this temperature cycle.

Table 6.2: Gneiss Point weight loss after above zero temperature cycles

Moisture Level	No. of Replicates	Weight Loss			
		Mean (g)	Standard Deviation (g)	Significance	Proportional weight loss ($x10^{-5}$)
No Moisture	5	0.009	0.003	P<0.001	1.31
Half Saturation	5	0.028	0.016	P<0.010	3.73
Full Saturation	5	0.025	0.023	P<0.039	3.48

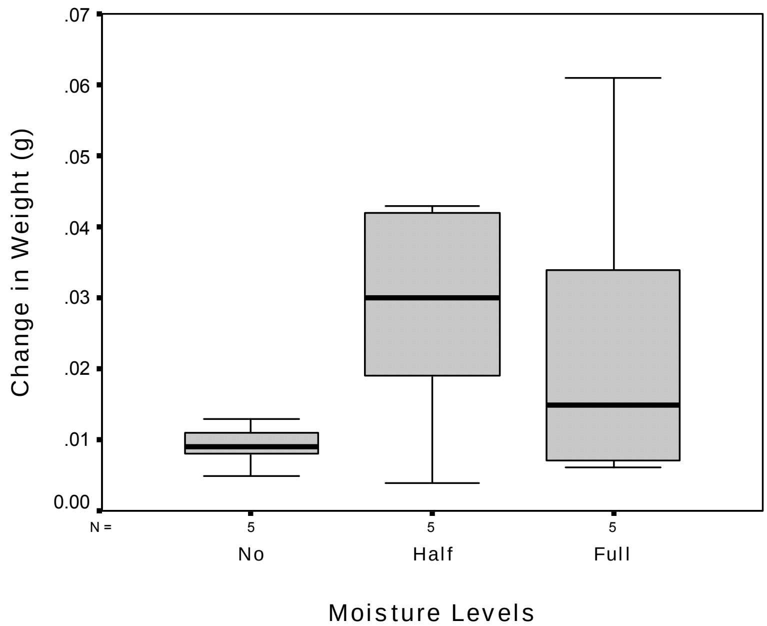

Figure 6.1: Box and Whisker plots for Gneiss Point indicating the variability in weight loss of the individual samples by moisture level following the above zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.3: Gneiss Point effective porosity and ultrasonic velocity after above zero temperature cycles

Moisture Level	Effective Porosity			Ultrasonic Velocity (after 10 measurements in each direction)			
	Initial (%)	After Above Cycles (%)	Sig.	Mean Change for Length (m/s)	Sig.	Mean Change for Breadth (m/s)	Sig.
No Moisture	0.44	0.42	n.s.	+13.4	n.s.	+173.0	n.s.
Half Saturation	0.47	0.44	n.s.	+49.4	n.s.	+75.4	n.s.
Full Saturation	0.73	0.67	P<0.017	+195.2	P<0.008	+118.2	n.s.

6.3.2 Aggregates

The proportion of particles in the less than 2 mm diameter size range increased with increasing moisture level for both Terra Nova Bay and Gneiss Point and all weight losses at the individual moisture levels were significant (Table 6.4). However, the losses under the no moisture scenario were less than might have been expected for sieving alone (0.52 g; 0.003%). A series of graphs comparing particle size distributions before and after the temperature cycles showed little if any change within the different particle size groups and Figure 6.2 is shown as an example. There was a statistically significant moisture effect for Terra Nova Bay and Gneiss Point but this could not be determined for Teall Island as the no moisture and half saturation samples were corrupted.

Table 6.4: Increase in particles less than 2 mm in diameter after above zero temperature cycles

Location	Moisture Level					
	No		Half		Full	
	gms	%	gms	%	gms	%
Terra Nova Bay	0.45*	0.08	1.58*	0.28	2.02*	0.35
Gneiss Point	0.48*	0.08	0.59*	0.09	1.18*	0.19
Teall Island	n/a	n/a	n/a	n/a	1.48*	0.24

* significant at p< 0.05; n/a = not available

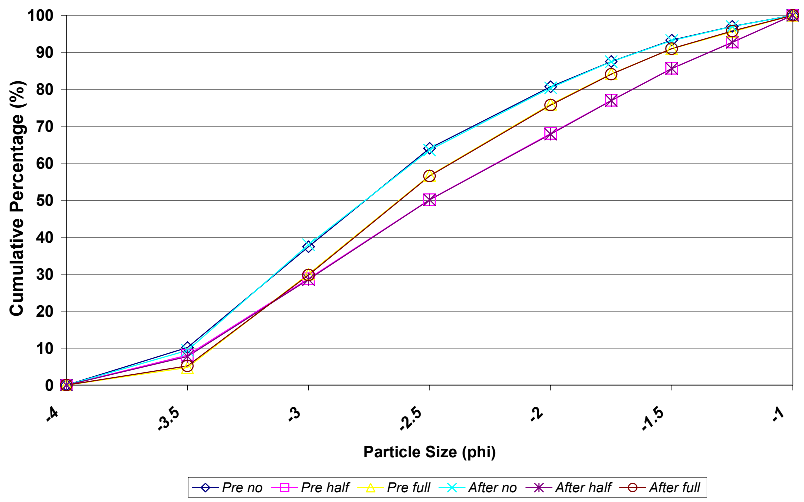

Figure 6.2: Terra Nova Bay cumulative aggregate particle size distribution indicating distribution pre the experiment and after the above zero temperature cycles for each moisture level

6.4 Across Zero Temperature Cycles

6.4.1 Rock Blocks

Both the Terra Nova Bay half saturated and fully saturated samples experienced statistically significant weight loss after the across zero temperature cycles. The greatest proportional weight loss was for the half saturated samples (Table 6.5). Figure 6.3 indicates that the variability of the individual samples were relatively consistent. Effective porosity decreased for the no moisture and half saturated samples but there was no significant change for the fully saturated samples. Ultrasonic velocity increased for both the half saturated and fully saturated samples (Table 6.6).

Table 6.5: Terra Nova Bay weight loss after across zero temperature cycles

Moisture Level	**No. of Replicates**	**Weight Loss**			
		Mean (g)	**Standard Deviation (g)**	**Significance**	**Proportional weight loss ($x10^{-5}$)**
No Moisture	3	0.009	0.007	n.s.	1.29
Half Saturation	4	0.038	0.010	P<0.003	5.81
Full Saturation	4	0.035	0.009	P<0.003	5.22

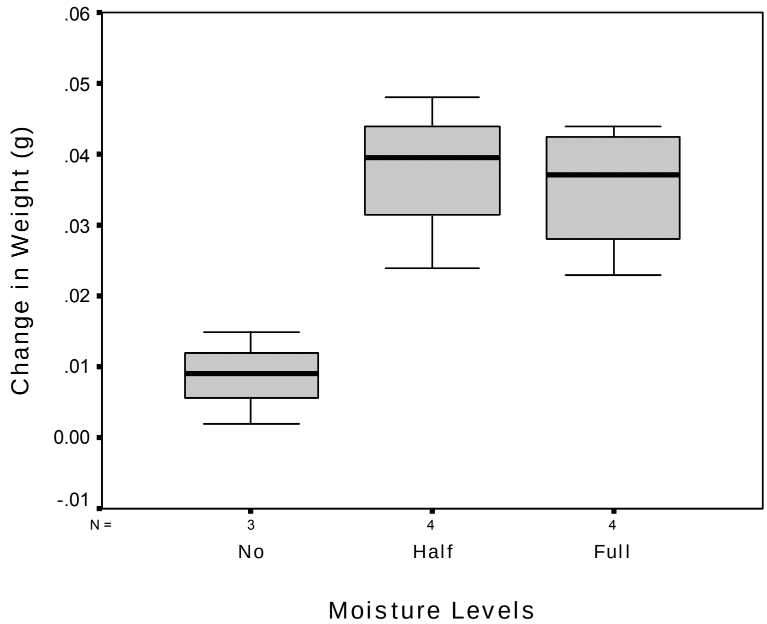

Figure 6.3: Box and Whisker plots for Terra Nova Bay indicating the variability in weight loss of the individual samples by moisture level following the across zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.6: Terra Nova Bay effective porosity and ultrasonic velocity after across zero temperature cycles

Moisture Level	Effective Porosity			Ultrasonic Velocity (after 10 measurements in each direction)			
	Initial (%)	After Across Cycles (%)	Sig.	Mean Change for Length (m/s)	Sig.	Mean Change for Breadth (m/s)	Sig.
No Moisture	1.23	1.18	P<0.007	-6.4	n.s.	-49.6	n.s.
Half Saturation	1.23	1.20	P<0.018	+81.4	P<0.029	+67.4	n.s.
Full Saturation	1.27	1.28	n.s.	+78.0	P<0.044	+114.6	P<0.042

All moisture levels showed a significant weight loss for the Gneiss Point samples and there was a decreasing trend in proportional weight loss with moisture level (Table 6.7). The individual variability of the samples is shown in Figure 6.4. There were no significant changes in ultrasonic velocity but the no moisture and fully saturated samples indicated a significant increase in effective porosity (Table 6.8).

Table 6.7: Gneiss Point weight loss after across zero temperature cycles

Moisture Level	**No. of Replicates**	**Weight Loss**			
		Mean (g)	**Standard Deviation (g)**	**Significance**	**Proportional weight loss ($x10^{-5}$)**
No Moisture	5	0.027	0.008	P<0.001	3.91
Half Saturation	5	0.018	0.010	P<0.008	2.46
Full Saturation	5	0.011	0.011	P<0.047	1.50

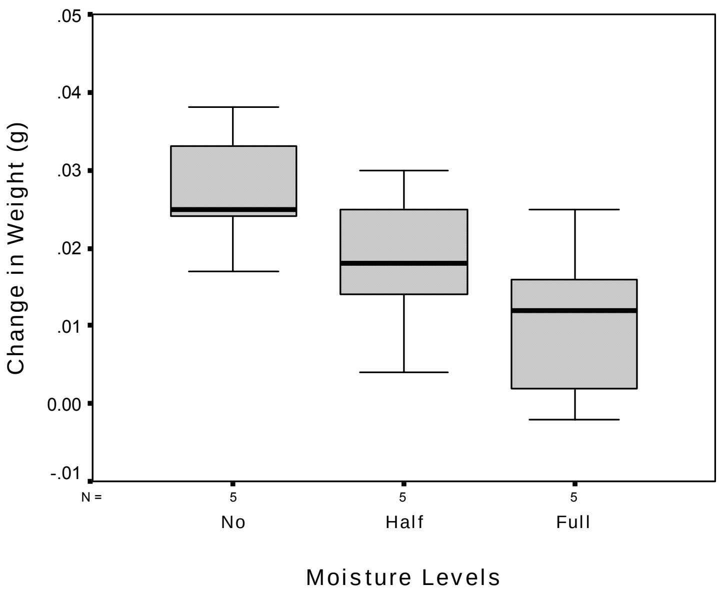

Figure 6.4: Box and Whisker plots for Gneiss Point indicating the variability in weight loss of the individual samples by moisture level following the across zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.8: Gneiss Point effective porosity and ultrasonic velocity after across zero temperature cycles

Moisture Level	**Effective Porosity**			**Ultrasonic Velocity** (after 10 measurements in each direction)			
	Before Across Zero Cycles (%)	**After Across Zero Cycles (%)**	**Sig.**	**Mean Change for Length (m/s)**	**Sig.**	**Mean Change for Breadth (m/s)**	**Sig.**
No Moisture	0.42	0.43	P<0.032	-2.4	n.s.	-323.4	n.s.
Half Saturation	0.44	0.47	n.s.	+197.0	n.s.	+118.0	n.s.
Full Saturation	0.67	0.72	P<0.016	+107.6	n.s.	+55.2	n.s.

All Teall Island moisture levels experienced significant weight loss with the greatest proportional loss being for the half saturated samples (Table 6.9). Figure 6.5 indicates that there was one sample in each of the half saturation and full saturation replicates that were outliers. Only the no moisture samples experienced a significant change in ultrasonic velocity but both the no moisture and fully saturated samples experienced a significant decrease in effective porosity (Table 6.10).

Table 6.9: Teall Island weight loss after across zero temperature cycles

Moisture Level	**No. of Replicates**	**Weight Loss**			
		Mean (g)	**Standard Deviation (g)**	**Significance**	**Proportional weight loss ($x10^{-5}$)**
No Moisture	4	0.023	0.009	P<0.009	3.27
Half Saturation	5	0.035	0.014	P<0.003	4.88
Full Saturation	5	0.023	0.006	P<0.001	3.47

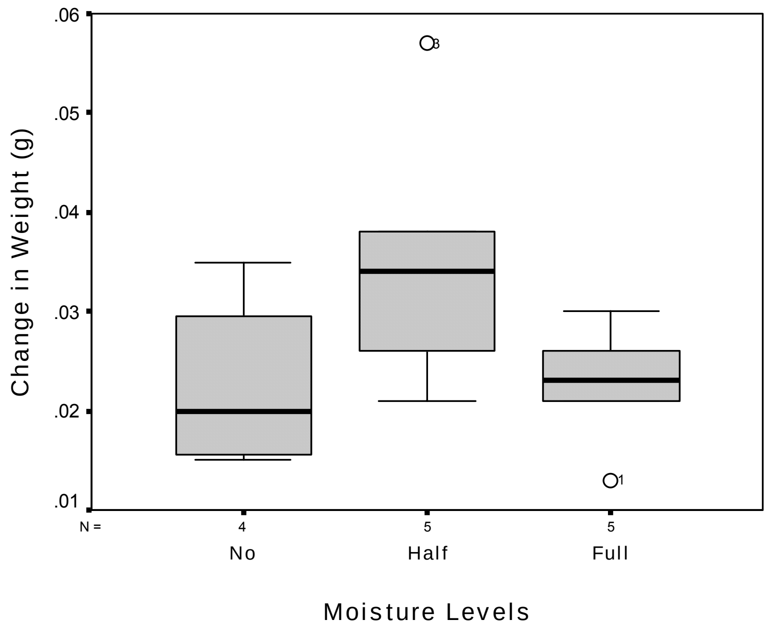

Figure 6.5: Box and Whisker plots for Teall Island indicating the variability in weight loss of the individual samples by moisture level following the across zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.10: Teall Island effective porosity and ultrasonic velocity after across zero temperature cycles

Moisture Level	Effective Porosity			Ultrasonic Velocity (after 10 measurements in each direction)			
	Before Across Zero Cycles (%)	After Across Zero Cycles (%)	Sig.	Mean Change for Length (m/s)	Sig.	Mean Change for Breadth (m/s)	Sig.
No Moisture	0.78	0.74	P<0.033	-61.6	P<0.028	-29.4	n.s.
Half Saturation	0.82	0.81	n.s.	-542.6	n.s.	+29.4	n.s.
Full Saturation	1.03	0.99	P<0.009	-148.8	n.s.	-11.6	n.s.

In summary, with the exception of the Terra Nova Bay no moisture samples, the across zero temperature cycles produced a statistically significant weight loss regardless of moisture level. Proportional weight loss was greatest for the half saturated samples for both Terra Nova Bay and Teall Island but was greatest for the no moisture Gneiss Point samples. Gneiss Point had the greatest proportional weight loss of all locations for the no moisture samples but Terra Nova Bay experienced the greatest proportional weight loss for both the half saturation and full saturation samples (Tables 6.5, 6.7 & 6.9). Figure 6.6 represents this graphically, although it should be noted that because all samples were subjected to the same air (freezer) temperature this should not be taken to necessarily imply a latitudinal effect and this is discussed further in Chapter 7. In addition, the error bars indicate that the differences between the half and full saturation weight loss could be due to experimental error (Figure 6.6).

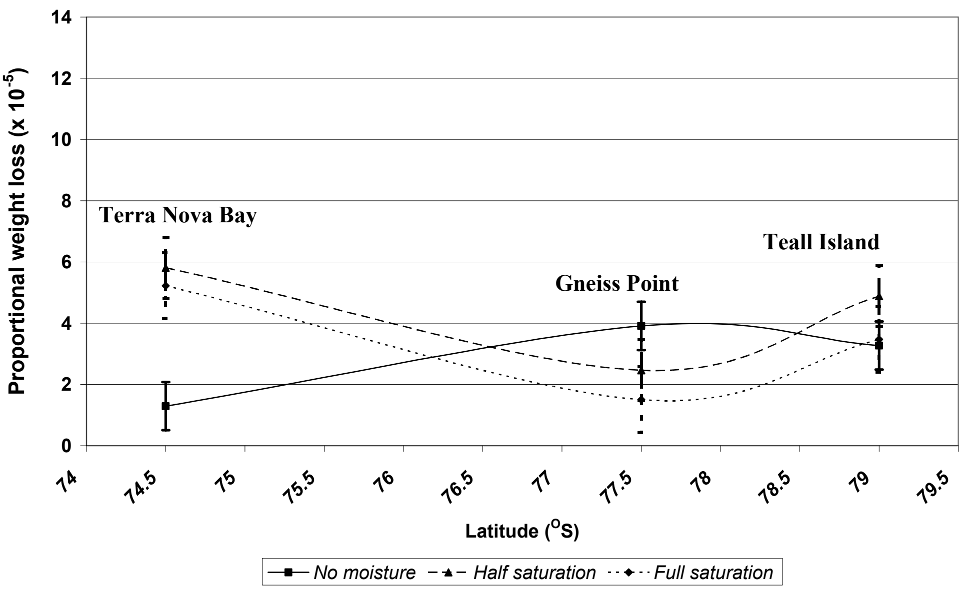

Figure 6.6: Proportional weight loss for the across zero temperature cycles by latitude. Error bars are ± 1 S.E. from the mean

Changes in effective porosity differed with rock type but where statistically significant change did occur, the Terra Nova Bay and Teall Island samples displayed a decrease whereas the Gneiss Point samples experienced an increase. All three locations experienced significant changes in effective porosity in the no moisture samples but only Terra Nova Bay experienced a change for the half saturated samples. Both Gneiss Point and Teall Island had significant change in porosity for the fully saturated samples but Gneiss Point had an increase whereas Teall Island had a decrease. Ultrasonic wave velocity increased in the Terra Nova Bay half and fully saturated samples but the Teall Island no moisture samples decreased, there were no significant changes in the Gneiss Point samples (Tables 6.6, 6.8 & 6.10).

6.4.2 Aggregates

Moisture had an increasing effect on weight loss for the across zero temperature cycles at Gneiss Point but maximum effect was for the half saturated samples at Terra Nova Bay. With the exception of the fully saturated samples at Terra Nova Bay all weight loss at the individual moisture levels were significant (Table 6.11). There was no moisture effect for the Terra Nova Bay across zero cycles but there was for the Gneiss Point ones. No significant change could be detected in the particle size distributions. Again the no moisture samples experienced weight loss less than that determined as a result of sieving alone.

Table 6.11: Increase in particles less than 2 mm in diameter after across zero temperature cycles

Location	Moisture Level					
	No		Half		Full	
	gms	%	gms	%	gms	%
Terra Nova Bay	0.47*	0.08	1.41*	0.26	1.10	0.19
Gneiss Point	0.46*	0.07	0.70*	0.11	1.39*	0.23
Teall Island	n/a	n/a	n/a	n/a	1.51*	0.25

* significant at $p < 0.05$; n/a = not available

6.5 BELOW ZERO CYCLES

6.5.1 Rock Blocks

All Terra Nova Bay moisture levels experienced a statistically significant decrease in weight following the below zero temperature cycles with the greatest proportional change occurring in the no moisture samples (Table 6.12). Individual sample variability is indicated in Figure 6.7. There were no significant changes in ultrasonic velocity but effective porosity increased significantly for the no moisture and half saturated samples (Table 6.13).

Table 6.12: Terra Nova Bay weight loss after below zero temperature cycles

Moisture Level	No. of Replicates	Weight Loss			
		Mean (g)	Standard Deviation (g)	Significance	Proportional weight loss ($x10^{-5}$)
No Moisture	3	0.057	0.005	P<0.002	8.52
Half Saturation	4	0.038	0.014	P<0.007	5.81
Full Saturation	4	0.047	0.016	P<0.005	7.00

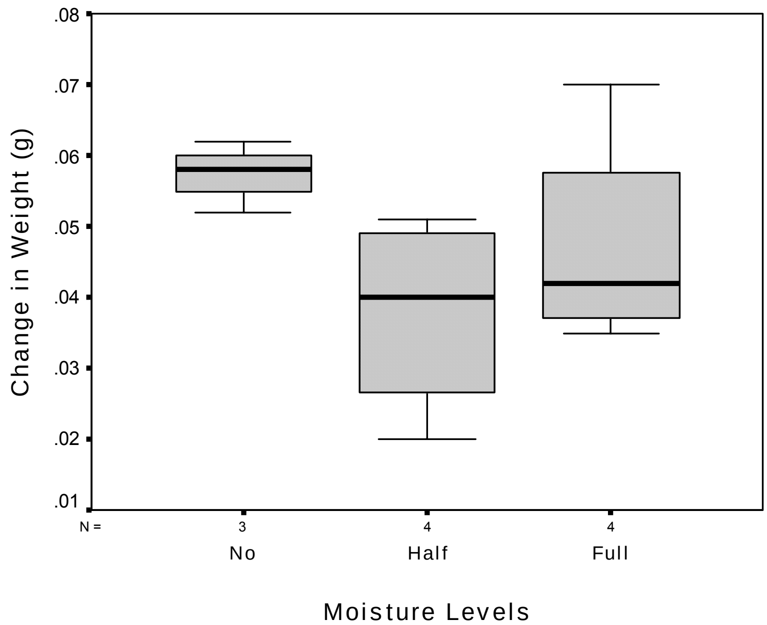

Figure 6.7: Box and Whisker plots for Terra Nova Bay indicating the variability in weight loss of the individual samples by moisture level following the below zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.13: Terra Nova Bay effective porosity and ultrasonic velocity after below zero temperature cycles

Moisture Level	**Effective Porosity**			**Ultrasonic Velocity (after 10 measurements in each direction)**			
	Before Below Zero Cycles (%)	**After Below Zero Cycles (%)**	**Sig.**	**Mean Change for Length (m/s)**	**Sig.**	**Mean Change for Breadth (m/s)**	**Sig.**
No Moisture	1.18	1.27	P<0.001	-24.6	n.s.	+15.8	n.s.
Half Saturation	1.20	1.26	P<0.032	-29.6	n.s.	-7.8	n.s.
Full Saturation	1.28	1.32	n.s.	+24.0	n.s.	-48.0	n.s.

As for Terra Nova Bay, all Teall Island moisture levels had a significant loss in weight but proportional weight loss increased with increasing moisture level (Table 6.14). Boxplots indicate the variability in results for the individual samples. Effective porosity increased for all moisture levels but only the no moisture samples indicated a change in ultrasonic velocity (Table 6.15).

Table 6.14: Teall Island weight loss after below zero temperature cycles

Moisture Level	**No. of Replicates**	**Weight Loss**			
		Mean (g)	**Standard Deviation (g)**	**Significance**	**Proportional weight loss ($x10^{-5}$)**
No Moisture	4	0.022	0.010	P<0.011	3.13
Half Saturation	5	0.024	0.009	P<0.002	3.35
Full Saturation	5	0.029	0.018	P<0.013	4.45

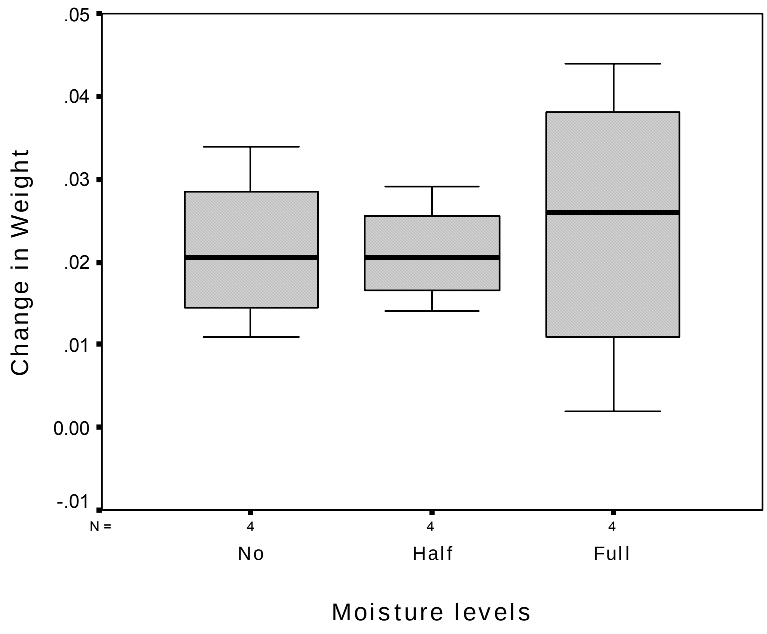

Figure 6.8: Box and Whisker plots for Teall Island indicating the variability in weight loss of the individual samples by moisture level following the below zero temperature cycles. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

Table 6.15: Teall Island effective porosity and ultrasonic velocity after below zero temperature cycles

Moisture Level	Effective Porosity			Ultrasonic Velocity (after 10 measurements in each direction)			
	Before Below Zero Cycles (%)	After Below Zero Cycles (%)	Sig.	Mean Change for Length (m/s)	Sig.	Mean Change for Breadth (m/s)	Sig.
No Moisture	0.74	0.79	P<0.006	+48.4	n.s.	+75.6	P<0.020
Half Saturation	0.81	0.85	P<0.002	+31.2	n.s.	+1.4	n.s.
Full Saturation	0.99	1.05	P<0.004	+48.2	n.s.	+26.4	n.s.

In summary, the below zero temperature cycles produced significant weight loss for rock samples from both locations and for all moisture levels. Proportional weight loss was greatest for the no moisture Terra Nova Bay samples and for the Teall Island fully saturated samples (Tables 6.12 & 6.14). Effective porosity increased for all moisture levels at both sites with all but the Terra Nova Bay fully saturated samples showing a statistically significant difference. Only the Teall Island no moisture samples showed a significant change (increase) in ultrasonic velocity (Tables 6.13 & 6.15).

6.6 Cumulative Effects

6.6.1 Rock Blocks

Statistically significant weight loss was experienced at all locations for all moisture levels when comparing the cumulative weight loss after all the temperature cycles with the initial weights. The maximum proportional weight loss at Terra Nova Bay was for the fully saturated samples but for Gneiss Point and Teall Island it was for the half saturated samples (Table 6.16). The Gneiss Point samples experienced less proportional weight loss for all moisture levels than Teall Island or Terra Nova Bay (Figure 6.9). Repeated measures analysis indicated that there was a statistically significant temperature cycle effect for all rock types but a moisture effect, between the no moisture and half saturation and the full saturation and half saturation samples, for Gneiss Point only.

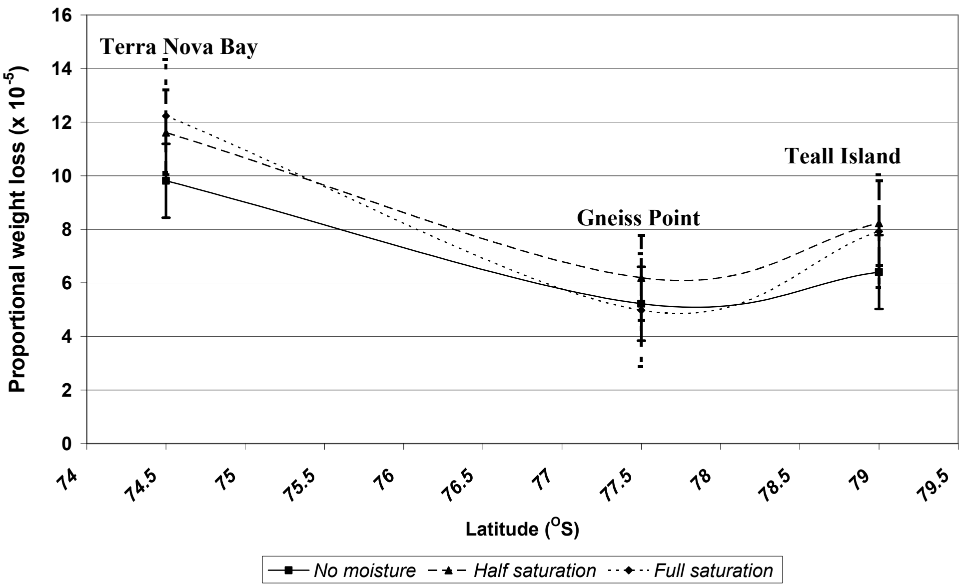

Figure 6.9: Proportional weight loss for the cumulative effect of all temperature cycles. Error bars are ± 1 S.E. from the mean

Table 6.16: Weight loss following all temperature cycles (where n is the number of replicates and s.d. is the standard deviation of the samples)

Moisture Level	Terra Nova Bay				Gneiss Point				Teall Island			
	n	Mean (g)	s.d.	Prop. wt loss ($x10^{-5}$)	n	Mean (g)	s.d.	Prop. wt loss ($x10^{-5}$)	n	Mean (g)	s.d.	Prop. wt loss ($x10^{-5}$)
No Moisture	3	0.066	0.002	9.81	5	0.037	0.010	5.22	4	0.044	0.004	6.40
Half Saturation	4	0.076	0.020	11.61	5	0.046	0.025	6.19	5	0.059	0.013	8.23
Full Saturation	4	0.083	0.019	12.23	5	0.035	0.029	4.98	5	0.052	0.024	7.92

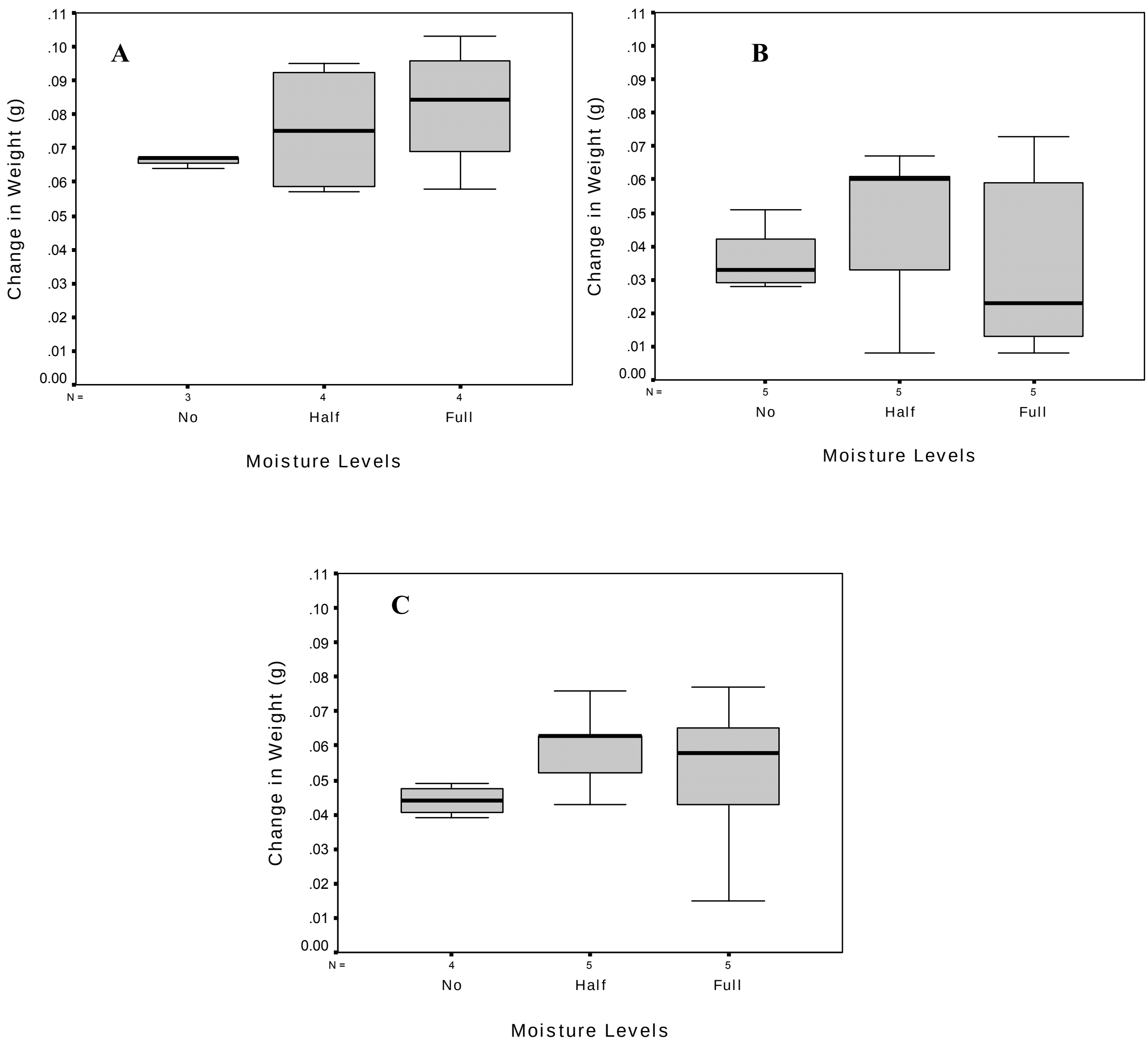

Figure 6.10: Box and Whisker plots for (A) Terra Nova Bay (B) Gneiss Point and (C) Teall Island indicating the variability in weight loss of the individual samples by moisture level at the end of the experiment. The heavy solid line is the median value, the box represents the inter-quartile range and the whiskers extend to the highest and lowest values excluding outliers and extremes (which have already been removed from this analysis)

With the exception of the Gneiss Point fully saturated samples, effective porosity increased in all cases where there was a statistically significant change (Table 6.17).

Table 6.17: Effective porosity after all temperature cycles compared to initial values

Moisture Level	Initial			After All Cycles					
	TNB	GP	TI	TNB		GP		TI	
	%	%	%	%	Sig.	%	Sig.	%	Sig.
No Moisture	1.23	0.44	0.78	1.27	P<0.007	0.43	n.s.	0.79	P<0.012
Half Saturation	1.23	0.47	0.82	1.26	n.s.	0.47	n.s.	0.85	P<0.004
Full Saturation	1.27	0.73	1.03	1.32	n.s.	0.72	P<0.021	1.05	n.s.

The Gneiss Point fully saturated samples experienced a significant increase in ultrasonic velocity (for the length measurements) whilst both the half and fully saturated samples at Terra Nova Bay experienced significant increases (Table 6.18).

Table 6.18: Changes in ultrasonic velocity after all temperature cycles compared to initial values (based on 10 measurements in each direction)

Moisture Level	**Terra Nova Bay**				**Gneiss Point**				**Teall Island**			
	Mean Change for Length (m/s)	**Sig.**	**Mean Change for Breadth (m/s)**	**Sig.**	**Mean Change for Length (m/s)**	**Sig.**	**Mean Change for Breadth (m/s)**	**Sig.**	**Mean Change for Length (m/s)**	**Sig.**	**Mean Change for Breadth (m/s)**	**Sig.**
No Moisture	-31.0	n.s.	-33.8	n.s.	+11.0	n.s.	-150.4	n.s.	-13.2	n.s.	+46.2	n.s.
Half Saturation	+51.8	n.s.	+59.6	$P<0.040$	+246.4	n.s.	+193.4	n.s.	-511.4	n.s.	+30.8	n.s.
Full Saturation	+102.0	n.s.	+66.6	$P<0.031$	+302.8	$P<0.006$	+173.4	n.s.	-100.6	n.s.	+14.8	n.s.

6.6.2 Aggregates

There was a significant increase in the less than 2 mm diameter particles size for all moisture levels at all locations. However, repeated measures analysis determined that there was both a cycle effect and a cycle x moisture interaction for both Terra Nova Bay and Gneiss Point. In other words, it was a combination of cycle and moisture level that was most effective in producing increases in the less than 2 mm diameter size group (Table 6.19). As noted in Sections 6.3.2 and 6.4.2 the weight loss experienced by the no moisture samples is less than that which could be expected as a result of sieving alone.

Overall the results of the laboratory experiment on the aggregates was less than had been expected from previous research (e.g. Fahey 1983). This was partly due to the loss of the Teall Island samples but also to the lack of change in the particle size distributions. Whilst there was an increase in particles less than 2 mm in diameter for all moisture levels there was no overall moisture effect.

Table 6.19: Increase in particles less than 2 mm in diameter after all cycles

Location	**Moisture Level**					
	No		**Half**		**Full**	
	gms	**%**	**gms**	**%**	**gms**	**%**
Terra Nova Bay	0.92*	0.16	2.99*	0.54	3.12*	0.54
Gneiss Point	0.95*	0.15	1.29*	0.21	2.58*	0.42
Teall Island	n/a	n/a	n/a	n/a	2.99*	0.49

* significant at $p < 0.05$; n/a = not available

6.7 SUMMARY AND INTERPRETATION OF RESULTS

6.7.1 Summary of Results

Key results were that:

- Statistically significant weight loss occurred in the rock blocks for all rock types and all moisture levels when the cumulative effect of the temperature cycles was taken into account
- There was a statistically significant temperature cycle effect for all rock types on weight loss but a moisture effect was only detected for Gneiss Point
- Proportional weight loss varied with rock type, moisture level and the type of temperature cycle and the greatest proportional weight loss in the rock blocks was not necessarily associated with the highest moisture level
- Effective porosity decreased, increased or experienced no change when comparing the final values with the initial values. However, the different temperature cycles had different effects so that an initial decrease in effective porosity could be followed by a subsequent increase
- Where a statistically significant difference occurred, ultrasonic velocity increased after all temperature cycling but only when additional moisture had been applied
- Each rock type responded differently to the experiment with some experiencing granular disintegration only whilst others had associated changes to pore space and/or micro-cracking
- There was a statistically significant moisture effect for the aggregates following the above zero cycles for both Terra Nova Bay and Gneiss Point but this was significant for Gneiss Point only following the across zero cycles
- The weight loss of the no moisture aggregates was always less than that expected by sieving alone, regardless of temperature cycle

6.7.2 Interpretation of Results

Rocks respond in a variety of ways to weathering depending on rock type, whether it is massive or not (Matsuoka, 2001a) and the processes involved (Nicholson, 2001). Small, hard, intact rocks and aggregates were used in this study so that the most likely weathering responses were: granular disintegration, flaking or micro-cracking. The opening of pore spaces generally was also a possibility. As discussed in Chapter 2, fatigue failure in hard rocks is likely to be by micro-crack expansion (Bland & Rolls, 1998) and a larger grained rock is also more susceptible to crack propagation (Attewell & Farmer, 1976). The strength of a rock is also affected by its porosity and its tensile strength reduces with increasing quartz content (Merriam et al., 1970).

Three measures were used to determine changes in the rock blocks: weight loss, effective porosity and ultrasonic velocity. Weight loss implies that some *surficial* physical weathering had taken place i.e., at least some measurable quantity of rock had fallen off the sample resulting in granular disintegration. Effective porosity measures the connectivity of the pores or micro-cracks to the external surface of the blocks (not necessarily to each other) and can be thought of as an *internal/surficial* measure. Consequently, any change in effective porosity is only a measure of change in the pores connected to the outside of the block and not necessarily total pore space. An increase in effective porosity indicates that additional pore spaces or micro-cracks have opened up. A decrease in effective porosity implies that some physical change has taken place at the surface to reduce the volume of externally connected voids *and/or* weathered material has filled some of the existing pore spaces or micro-cracks (Nicholson, 2001). It is also possible that salts may have been mobilised. Nicholson (2001) also suggested that some sort of pore compaction might have been a cause of the decreases in effective porosity found in the limestones she was investigating. However, although rocks do expand and contract, especially the less brittle ones, it is unlikely that either of these would occur in the hard rocks under consideration here.

The term void space is used here to mean either pore spaces or micro-cracks. Whilst joints or other major discontinuities would be included under this heading when considering massive rock, only pore spaces and micro-cracks are relevant to the study of small intact blocks as used in this experiment. Thin section analysis had revealed that the Teall Island and Terra Nova Bay rocks were extensively micro-cracked compared to Gneiss Point, where any cracks that were evident were filled (Table 4.8 and Figures 4.2, 4.6 & 4.8).

Ultrasonic velocity provides a measure of the *internal* structure of the rock and is an indirect measure of its density or strength. Air has a very low ultrasonic wave velocity compared to that of rock and so any decrease in velocity indicates that air has replaced rock and hence voids have opened up. Similarly, an increase in ultrasonic velocity implies that there has been a decrease in void space. A reconfiguration of existing material so that it blocks pores or micro-cracks will not reduce the total void space only that connected to the exterior. Consequently, an increase in ultrasonic velocity would only occur following substantial change to the exterior of the block or if there was a reconfiguration of the internal crack geometry. However, ultrasonic velocity is affected by moisture content and temperature and, although measurements were always undertaken on the samples after they had been dried to constant weight and then cooled, it is also possible that the rock blocks absorbed sufficient moisture during this process to affect the ultrasonic velocity results.

Changes in effective porosity and ultrasonic velocity can be thought of as changes in void space and Table 6.20 summarises the possible causes of increases and decreases in void space together with means of measurement. The rest of this section considers the results in the light of the first three research questions of this study.

Table 6.20: Interpretation of changes in void space by measure and possible cause

Change	Measured by	Possible cause
Increase in void space	▪ Increase in effective porosity ▪ Decrease in ultrasonic velocity	▪ Additional micro-cracking ▪ Flushing out of materials from existing cracks (additional moisture only)
Decrease in void space	▪ Decrease in effective porosity ▪ Increase in ultrasonic velocity	▪ External change following granular disintegration producing reduction in pore space accessible to exterior ▪ Blocking of pore/void space by reconfiguration of materials or mobilisation of salts (effective porosity only) ▪ Reconfiguration of internal crack geometry (ultrasonic only) ▪ Possible sample contamination (ultrasonic only)

Research Question 1: For a specific rock group what is the total weathering rate at each of the field sites?

External weathering, in the form of granular disintegration, occurred for all rock types and all moisture levels with the Terra Nova Bay rocks having the greatest proportional amount followed by Teall Island and then Gneiss Point for each moisture level (Figure 6.9, Table 6.21). Thin section analysis revealed that the former two were extensively micro-cracked whereas Gneiss Point was much less so. However, some rocks also experienced a change in void space as determined by either internal/external (i.e. as measured by effective porosity, Table 6.17) or internal (i.e. as measured by ultrasonic velocity, Table 6.18) weathering and Table 6.21 indicates that the rocks responded in three different ways to the experiment:

1. Granular disintegration only
2. Granular disintegration combined with an increase in void space
3. Granular disintegration combined with a decrease in void space

Granular disintegration combined with an increase in void space occurred at Terra Nova Bay (no moisture) and Teall Island (no moisture and half saturation). The increase in void space could be the result of additional micro-cracking or the flushing out of material from existing cracks or pore spaces. However, as this occurred in the no moisture samples from both rock types making it unlikely that this was a result of flushing out of material so it was concluded that this was in response to additional micro-cracking.

Table 6.21: Cumulative effect of all temperature cycles by type of change

Moisture Level	Weathering Change					
	Granular disintegration (proportional weight loss x 10^{-5})			Change in void space		
	Terra Nova Bay	Gneiss Point	Teall Island	Terra Nova Bay	Gneiss Point	Teall Island
No Moisture	9.81	5.22	6.40	↑	X	↑
Half Saturation	11.61	6.19	8.23	↓	X	↑
Full Saturation	12.23	4.98	7.92	↓	↓	X

X = no statistically significant change; ↑ = increase in void space; ↓ = decrease in void space

Granular disintegration with a decrease in void space occurred in three sets of samples: Gneiss Point full saturation, Terra Nova Bay half and full saturation (Table 6.21). The Gneiss Point full saturation samples experienced both a decrease in effective porosity and an increase in ultrasonic velocity implying that the change was either a result of an external change following granular disintegration or possibly pore blockage following the reconfiguration of materials or mobilisation of salts (Table 6.20). However, the material that was removed from the Gneiss Point fully saturated samples was very fine and unlikely to produce sufficient change to the exterior of the sample to influence either effective porosity or ultrasonic velocity, and so it was concluded that some sort of pore blockage had occurred (Figure 6.11).

Figure 6.11: Products of granular disintegration of Gneiss Point full saturation samples

However, the decrease in void space for the Terra Nova Bay samples was only in response to internal change (i.e., an increase in ultrasonic velocity) which could be the result of either an external change following granular disintegration, reconfiguration of internal cracking or possible sample contamination. As for Gneiss Point, the Terra Nova Bay half and fully saturated samples produced small granular disintegration and so it was concluded that the reduction in void space was either the result of changes in internal micro-crack configuration or sample contamination (Figure 6.12).

Figure 6.12: Products of granular disintegration of Terra Nova Bay no moisture samples

Therefore, at Terra Nova Bay granular disintegration and micro-cracking occurred for the no moisture level but granular disintegration together with internal changes took place in the presence of additional moisture. At Gneiss Point granular disintegration occurred in the no moisture and half saturation samples but granular disintegration accompanied by pore blockage, took place with full saturation. At Teall Island, granular disintegration only took place at the highest moisture level whereas granular disintegration accompanied by micro-cracking occurred in the no moisture and half saturation samples.

Reduction in void space occurred in the Terra Nova Bay (half and full saturation) and the Gneiss Point (full saturation) samples. These rocks have similar quartz and biotite contents (Table 4.3), chemical composition (Figure 4.10) and albedo (Table 4.5) and are different to the Teall Island rocks, which had lower proportions of quartz and biotite but higher silicon content and albedo than the other two types. Micro-cracking took place in the Terra Nova Bay (no moisture) and the Teall Island (no moisture and half saturation) samples. These two rock types are quite different except for grain size and susceptibility to micro-cracking, both of which are greater than in the Gneiss Point rocks (Table 4.8).

Estimates of weathering rates were made by calculating the amount of surface lowering (δx) of the rock blocks using the measured weight loss and the previously calculated density of the blocks[5]. The estimated rate was 0.16 x 10^{-3} mm a^{-1} overall but ranged from 0.11 (Gneiss Point) through 0.16 (Teall Island) to 0.23 (Terra Nova Bay) x 10^{-3} mm a^{-1}. These values are of the same order as those found by Summerfield et al. (1999) for the Dry Valleys and André (2002) for crystalline rocks in northern Scandinavia. Bland and Rolls (1998) also commented that laboratory weathering rates were up to a factor of 3 times more rapid than field results but this was not able to be tested here.

In summary, total weathering response was different for each rock type and moisture level. Where an increase in void space occurred, it was attributed to micro-cracking whereas decreases took place as a result of pore blockage or internal changes or possibly as an artefact of the experimental procedure when measuring ultrasonic velocity. Micro-cracking only occurred in the lower levels of moisture in those rocks with larger grain size and that were susceptible to micro-cracking. Void space reduction on the other hand occurred in those rocks that had similar mineral and chemical compositions, but only in those samples subjected to additional moisture, indicating that it was a combination of moisture and rock composition. The Gneiss Point rock has much lower sorptivity and moisture penetration values than the Terra Nova Bay ones and these may be the reasons that no decrease occurred in the half saturation samples (Table 4.8).

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[5] $\delta x = [\delta m/(\rho * \text{surface area})]/5$ where δm is the relevant weight loss and ρ is the density. The weight loss was produced over a simulated 5 years of weathering and so the equation is divided by 5.

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Research Question 2: What processes are operating in this environment and what are the weathering rates for specific processes?

Nicholson (2001) showed that different processes produced different weathering responses in sedimentary rock in her laboratory experiments. Frost weathering resulted in granular disintegration whereas salt weathering produced incipient fracturing. The processes under investigation here were frost weathering as determined by across zero cycles in the presence of additional moisture, thermal fatigue as determined by above or below temperature cycling in the no moisture samples and wetting and drying accompanied by temperature cycling as determined by the above or below zero cycling in the presence of additional moisture (Table 6.23). In the field the most likely processes were thermal shock, thermal fatigue, wetting and drying and possibly salt weathering (Table 3.6).

Table 6.23: Processes investigated described by the relevant temperature cycle and moisture level

Process	Temperature Cycle	Moisture Level
Frost weathering	Across	Half saturation Full saturation
Thermal fatigue	Above Below	No moisture
Wetting and drying & thermal fatigue	Above Below	Half saturation Full saturation

Frost weathering due to volumetric expansion is thought to occur in response to crossings of the zero degree isotherm and consequent expansion and contraction of the moisture in the rock as it freezes and thaws. It requires a high degree of saturation of the rock, a closed system and rapid freezing to operate effectively (Table 2.5). It is deemed to produce both granular disintegration and micro-cracking. Theoretically, the rocks are required to be almost fully saturated for volumetric expansion to occur and so it would be expected that the fully saturated samples in this experiment would produce the greatest response. However, this was not the case, with the greatest proportional loss being for the half saturation moisture level, regardless of rock type (Table 6.24). Consequently, either some other process was operating or the temperature cycling was overriding the effects of volumetric expansion.

Walder and Hallet (1985, 1986) argued that it was not volumetric expansion but ice segregation that was the cause of frost weathering and this has been supported by experimental work (e.g. Matsuoka, 1990a). The most effective temperature range for frost weathering of granite was calculated as -4 ^{O}C to -15 ^{O}C depending on crack geometry. For pre-existing cracks approximately 50 mm in length it was -4 ^{O}C to -7 ^{O}C and for those 5 mm in length -11 ^{O}C to -16 ^{O}C (Hallet et al., 1991). The Gneiss Point rocks did not experience these sorts of temperatures but the Terra Nova Bay and Teall Island ones did (Table 6.1). However, the process requires an ongoing supply of moisture and relatively porous and permeable rocks which was not the case here.

Table 6.24: Total weathering by frost

Location and Cycle	**Granular Disintegration (proportional weight loss x 10^{-5})**		**Change in Void Space**	
	Half Saturation	**Full Saturation**	**Half Saturation**	**Full Saturation**
Gneiss Point (across zero cycle)	2.46	1.50	X	↑
Terra Nova Bay (across zero cycle)	5.81	5.22	↓	↓
Teall Island (across zero cycle)	4.88	3.47	X	↓

X = no statistically significant change; ↑ = increase in void space; ↓ = decrease in void space

Proportionally, Gneiss Point experienced the least, and Terra Nova Bay the most weight loss of the three rock types under thermal fatigue (Table 6.25). Thermal cycling resulted in granular disintegration only in the Gneiss Point samples but was accompanied by an increase in void space at Terra Nova Bay. Since the samples had not been subjected to additional moisture it was concluded this was a result of micro-cracking. At Teall Island the samples experienced both an increase in effective porosity *and* an increase in ultrasonic velocity. This could only occur if there was sufficient change to the exterior of the block following granular disintegration to affect the ultrasonic velocity results combined with micro-cracking (Table 6.21). An examination of the material produced by granular disintegration suggests that this may be the case. Therefore, thermal cycling resulted in either granular disintegration only or granular disintegration plus micro-cracking, consistent with fatigue failure in hard rocks (Bland & Rolls, 1998).

Table 6.25: Total weathering by thermal fatigue

Location and Cycle	Granular Disintegration (proportional weight loss x 10^{-5})	Change in Void Space	Thermal Conductivity and Diffusivity
Gneiss Point (above zero cycle)	1.31	X	middle
Terra Nova Bay (below zero cycle)	8.52	↑	highest
Teall Island (below zero cycle)	3.13	?	lowest

X = no statistically significant change; ↑ = increase in void space; ↓ = decrease in void space

There are two ways that repeated heating and cooling can produce rock breakdown. The first is the build up of stresses in the rock in response to the different thermal expansion coefficients of the individual minerals. For example, quartz has a thermal expansion twice that of plagioclase or biotite at 20 ^{O}C (Saxena et al., 1993 cited in Warke, 2000). In addition, quartz itself expands half as much again in a direction normal to the c-axis compared to parallel (Bland & Rolls, 1998). At the rock surface this is likely to produce granular disintegration but deeper in the rock micro-cracking could result.

Thermal conductivity measures the ease with which heat is transferred through the rock and thermal diffusivity measures the rate at which it is transferred. If thermal conductivity and diffusivity are low then heat will be retained at the surface of the rock and stresses will build up between the outer, warmer layer of the rock, and the cooler inner layer (or vice-versa). This would result in surface flaking as well as granular disintegration in response to the different coefficients of thermal expansion of the minerals. Higher values of thermal conductivity and diffusivity indicate that larger quantities of heat are transferred more rapidly and the rock will be relatively equally heated throughout so that, as well as flaking and granular disintegration at the surface micro-cracking could also occur. Therefore it would be expected that the Teall Island rocks, with the lowest thermal values (for the west-facing site) would have experienced only granular disintegration but this was not the case (Table 6.24). In fact it was Gneiss Point with higher values that only experienced granular disintegration. Consequently, it was concluded that grain size and extent of previous micro-cracking were the significant factors. However, it should be noted that the values of thermal diffusivity and conductivity were calculated estimates and should be regarded as indicative only (Section 4.4).

Hall and Hall (1996) argued that it was humidity fluctuations alone that produced expansion and contraction of the rock resulting in rock breakdown. Dunn and Hudec (1966) on the other hand suggested that the ordered water hypothesis worked in the presence of clays. Wetting and drying in the Gneiss Point samples produced a decrease in void space in conjunction with granular disintegration but void space increased in the Terra Nova Bay and Teall Island samples (Table 6.26). A decrease in void space could be the result of the blocking of pore space by released material in the Gneiss Point samples (which had evidence of filled micro-cracks) as external changes due to granular disintegration were discounted earlier (Table 6.20).

Table 6.26: Total weathering by wetting and drying in conjunction with temperature cycling

Location and Cycle	**Granular Disintegration (proportional weight loss x 10^{-5})**		**Change in Void Space**	
	Half Saturation	**Full Saturation**	**Half Saturation**	**Full Saturation**
Gneiss Point (above zero cycle)	3.73	3.48	X	↓
Terra Nova Bay (below zero cycle)	5.81	7.00	↑	X
Teall Island (below zero cycle)	3.35	4.45	↑	↑

X = no statistically significant change; ↑ = increase in void space; ↓ = decrease in void space

The Terra Nova Bay and Teall Island samples experienced increases in effective porosity only, which could be a result of micro-cracking or the flushing out of materials (Tables 6.20 & 6.26). These rocks were not only larger grained but also had higher porosity, greater sorptivity and more rapid moisture penetration than the Gneiss Point ones (Tables 4.2 & 4.7). In addition, there was some evidence of clays in the thin section analysis (Table 4.8). Therefore it was suggested that the different response of the rock was because of the ability of moisture to penetrate the rock so that where there was little penetration, granular disintegration and void reduction occurred but where there was high and rapid penetration in the presence of clays, granular disintegration was accompanied by micro-cracking or the flushing out of materials from within the rock. However, it should be noted that the Gneiss Point samples experienced above zero cycling whereas the Terra Nova Bay and Teall Island rocks experienced below zero cycling and this difference may have affected the results.

The rocks could also have been responding to the combined effects of temperature cycling and wetting and drying. In the Gneiss Point rocks the addition of moisture produced more granular disintegration as well as void reduction. However, the Terra Nova Bay rocks experienced less granular disintegration following the addition of moisture but indicated that micro-cracking or the flushing out of existing material had also taken place. As for Gneiss Point the Teall Island rocks showed an increase in granular disintegration with additional moisture but this was accompanied by the same changes that took place in the Terra Nova Bay rocks. Therefore, the Gneiss Point and Teall Island rocks had increased granular disintegration above that experienced as a result of thermal fatigue but Gneiss Point also experienced a reduction in void space whereas Teall Island had an increase in void space. The Terra Nova Bay rocks had a decrease in granular disintegration but an increase in void space following wetting and drying.

In summary, frost weathering, as determined by weight loss, in the rocks following 354 across zero cycles, was most effective for the half saturation moisture level, regardless of rock type. However, other changes in the rocks were not so clear and resulted in increases, decreases or no change in void space depending on rock type (Table 6.24). These results are consistent with those of Nicholson (2001) for her sedimentary rocks under freeze-thaw conditions.

Thermal fatigue was most effective in the Terra Nova Bay rocks where it also resulted in an increase in void space as a result of micro-cracking. It was expected that, due to the basic premises of thermal fatigue, that Teall Island would only have produced granular disintegration but this was not the case and it was concluded that grain size and extent of previous micro-cracking were more important factors in controlling thermal fatigue than the thermal properties of the rock.

Wetting and drying affected the three rock types differently. Whilst all experienced granular disintegration, those with larger grain size and higher porosity, sorptivity and moisture penetration as well as previous micro-cracking also experienced increases in void space. This was a result of either additional micro-cracking or flushing out of existing material in the void spaces. The Gneiss Point rock, with its low capacity to absorb moisture as well as previous evidence of altered material in the small number of micro-cracks also experienced void reduction. A comparison of the results of wetting and drying with those of thermal fatigue indicated that Gneiss Point and Teall Island had an increased amount of granular disintegration whereas Terra Nova Bay had less, but other changes were variable.

Estimates of weathering rate, using the same approach as in the previous section and based on the rationale of Table 6.27, were also calculated for each of the processes investigated. These indicated that thermal fatigue was the most effective process for the Terra Nova Bay rocks, frost weathering for the Teall Island rocks and wetting and drying in conjunction with thermal fatigue the most effective for the Gneiss Point samples. The greatest weathering rate overall was for thermal fatigue at Terra Nova Bay (0.17×10^{-3} mm a^{-1}).

Table 6.27: Estimated weathering rates for individual processes as determined by the temperature and moisture conditions in Table 6.23

	Estimated Weathering Rate ($x\ 10^{-3}$ mm a^{-1})		
	Frost Weathering	**Thermal Fatigue**	**Wetting & Drying with Thermal Fatigue**
Terra Nova Bay	0.11	0.17	0.13
Gneiss Point	0.04	0.03	0.08
Teall Island	0.09	0.06	0.08

Research Question 3: Are there temperature and/or moisture regimes for which physical weathering is most effective?

The overall results of the experiment by moisture level and temperature cycle are given in Table 6.28. This indicates that the individual moisture levels produced differing effects:

1. No moisture: granular disintegration only *or* granular disintegration plus micro-cracking *or* a reduction in void space because of external changes or pore blockage
2. Half saturation: granular disintegration only *or* granular disintegration plus pore blockage *or* granular disintegration plus an increase in void space because of micro-cracking or the flushing out of material from pores
3. Full saturation: granular disintegration only *or* granular disintegration plus pore blockage or granular disintegration plus an increase in void space because of micro-cracking or flushing out of material from pores

Table 6.28: Weathering response by temperature cycle and moisture level

Cycle and Location	Moisture Level					
	No moisture		Half saturation		Full saturation	
	Granular Disinteg-ration	*Other Change*	*Granular Disinteg-ration*	*Other Change*	*Granular Disinteg-ration*	*Other Change*
Above zero cycles Gneiss Point	1.31	X	3.73	X	3.48	Void blocking
Across zero cycles						
Terra Nova Bay	1.29*	External or void blocking	5.81	Void blocking	5.22	Void blocking
Gneiss Point	3.91	Micro-cracking	2.46	X	1.50	Micro-cracking or flushing
Teall Island	3.27	Micro-cracking	4.88	X	3.47	Void blocking
Below zero cycles						
Terra Nova Bay	8.52	Micro-cracking	5.81	Micro-cracking or flushing	7.00	X
Teall Island	3.13	Micro-cracking	3.35	Micro-cracking or flushing	4.45	Micro-cracking or flushing

* = not significant at $p< 0.05$; X = no statistically significant change; ↑ = increase and ↓ = decrease in void space

Below zero temperature cycles invariably produced an increase in void space regardless of rock type or moisture level whereas above zero cycles only resulted in void reduction for the highest moisture level. Across zero cycles produced a variety of responses with reduction in void space in the Terra Nova Bay samples regardless of moisture level but an increase in void space for the Gneiss Point samples regardless of moisture level. However, the Teall Island rocks experienced both an increase and decrease in void space or no change depending on moisture level.

The above discussion has focussed on total weathering, weathering by individual processes and weathering produced by different moisture levels and temperature cycles. However, one additional result was that by considering only the overall effect of the experiment changes that occurred following individual temperature cycles could be masked. For example, although void space generally decreased after the first set of temperature cycles and then increased after the second set the total change could be either an increase or a decrease depending on the magnitude of the earlier changes (e.g. Terra Nova Bay no moisture and half saturation). On other occasions there appeared to be no change after both sets of cycles even though there had been changes during both earlier cycles. For instance, the Teall Island fully saturated samples had a significant decrease in effective porosity after the across temperature cycles, a significant increase after the below zero temperature cycles but indicated no significant change when overall results were compared to the initial values.

6.8 Implications for cold climate weathering

Griggs (1936) found no evidence that temperature cycling alone in the absence of moisture, produced rock breakdown. However, in this experiment granular disintegration (weight loss) occurred after above zero temperature cycling in the Gneiss Point samples regardless of moisture level. This implied that weathering could take place even in the absence of crossings of the zero degree isotherm (in the rock) and of additional moisture. However, the absolute humidity in the freezer, although low, was still measurable and changed with the temperature indicating that above zero temperature cycling, in conjunction with humidity fluctuations is capable of producing weathering changes in the rock. This provides support for the work of Dunn & Hudec (1966) and Fahey (1983) who argued that hydration shattering alone, even in the absence of clays, could cause rock breakdown. In addition, the rate of change of temperature during the experiment was 3-4 $^{O}C\ hr^{-1}$, which is much less than the threshold value for thermal shock (>2 $^{O}C\ min^{-1}$; Yatsu 1988) indicating that rapid rates of temperature change may not be required to produce rock breakdown.

There was evidence that both internal and internal/external changes occurred in the fully saturated Gneiss Point samples during the above zero temperature cycling, although both indicated a reduction in void space. Combined with external changes it is possible this is due to a reconfiguring of void space following granular disintegration. However, there was little evidence of external change in the samples so that these results appear to confirm that the pores have been blocked in some way, perhaps as a result of salt crystal growth. This is consistent with the results of Nicholson (2001) for across zero cycling on sedimentary rocks and suggests that high levels of moisture may produce weathering effects over and above external weight loss in the Gneiss Point rock even over a relatively short time interval and without freeze-thaw.

There has been considerable debate about the weathering mechanisms that operate when across zero temperature cycling takes place (e.g. McGreevy, 1981; Ballantyne & Harris, 1994; Hall 2004). Recently, Sass (2004) found evidence of pore water being pushed into limestone by expanding ice, supporting the views of McGreevy & Whalley (1985), and of water movement towards a freezing front, consistent with the views of Walder & Hallet (1985) on ice lens segregation. However, others still support the idea that the 9% expansion of water on freezing is the primary mechanism of rock breakdown in cold climates (e.g., Matsuoka, 2001b). Regardless of proposed mechanism, what is common to all the above is the need for sufficient water to either saturate the surface of the rock (Powers, 1945), to migrate and form ice lenses (Walder & Hallet, 1985; 1986) or at least be available for expansion (Matsuoka, 2001b). Various levels of saturation have been suggested as being required and Prick (1997) found that the critical degree of saturation for frost weathering ranged from 58% to 100% in her limestone samples. However, in this experiment, humidity fluctuations alone i.e., in the absence of additional moisture, produced statistically significant weight loss in the Gneiss Point and Teall Island samples for the across zero temperature cycles. Where moisture was applied the half saturated samples produced greater proportional weight loss than the fully saturated ones, indicating that high levels of saturation may not be required for active frost weathering to occur.

Granular disintegration was also evident for all moisture levels at both Terra Nova Bay and Teall Island for the below zero temperature cycles. In addition, changes in void space as determined by changes in effective porosity occurred for all but the Terra Nova Bay fully saturated samples. Again this indicated that repeated temperature cycling, even when it is below zero degrees can produce a weathering effect and that the type, magnitude and location of that effect differs depending on the characteristics of the rock. The greatest proportional weight loss for the Terra Nova Bay samples was for the below zero no moisture samples, providing some support for the work of Walder and Hallet (1986) who theorised that the most effective temperatures for weathering of granite was -4 to -15 ^{O}C. However, this was not the case for the highly sorptive Teall Island rock which had its greatest proportional effect for the half saturated samples in the frost weathering experiment. Nevertheless, Akagawa & Fukuda (1991) and Sass (2004) have shown that ice lenses can form without saturation.

Of particular importance to the Latitudinal Gradient Project is the potential effect of changes in climate on rock breakdown and it is the cumulative effects of the temperature cycles that is of interest. Whilst the individual rocks may have had different temperature regimes during these experiments the freezer temperature was consistent and can be regarded as air temperature. This set of experiments indicated that, under the same climatic conditions, more physical weathering occurred at Terra Nova Bay than either Teall Island or Gneiss Point and that the presence of additional moisture enhanced the weathering effect (Figure 6.9). These results imply that an increase in precipitation could produce additional rock breakdown at all of these locations particularly at Terra Nova Bay, but that it does not require high levels of saturation for this to occur (Figures 6.6 & 6.9). The finding of a main cycle effect for all rock types indicated that regardless of moisture level a change in the ratio of temperature cycles would produce a change in weathering rate.

The summer and spring/autumn temperature cycles also had a different effect on weathering for the three locations and were dependent on moisture level (Table 6.29). For example, at Terra Nova Bay the spring/autumn temperature cycles produced proportionally 6.6 times more weathering than the summer cycles for the no moisture samples but there was little difference between the two seasons for Teall Island at this moisture level. At Gneiss Point the spring/autumn cycles were 3 times more effective than the summer cycles for no applied moisture but they produced less than half the weathering of the summer cycles for the fully saturated samples. The implications of this are discussed in Chapter 7.

Table 6.29: Effect of different seasons on weathering intensity

Moisture Level and Location	Effect of summer cycles (+5 to -1.5 ^{O}C) (proportional weight loss x 10^{-5})	Effect of spring/autumn cycles (+1 to -8 ^{O}C) (proportional weight loss x 10^{-5})	Ratio of spring/autumn to summer
Terra Nova Bay			
No moisture	1.29	8.52	**6.6**
Half saturation	5.81	5.81	**1.0**
Full saturation	5.22	7.00	**1.3**
Gneiss Point			
No moisture	1.31	3.91	**3.0**
Half saturation	3.73	2.46	**0.7**
Full saturation	3.48	1.50	**0.4**
Teall Island			
No moisture	3.27	3.13	**1.0**
Half saturation	4.88	3.35	**0.7**
Full saturation	3.47	4.45	**1.3**

CHAPTER 7

PREDICTIVE MODEL AND WEATHERING INDEX

7.1 INTRODUCTION

This chapter addresses the fourth of the research questions: is there a relationship between weathering rate and latitude, as determined by moisture and temperature conditions, along the Victoria Land Coast? Section 7.2 discusses the general background to, as well as the development of, a model that could determine whether such a relationship might exist. It also explores how weathering might be affected at Terra Nova Bay, Gneiss Point and Teall Island under potential future climate change. Section 7.3 extends the model by developing a weathering index that takes into account many of the factors deemed to be important in determining rates of rock weathering. A comparison of the rates predicted by this index in the field and laboratory is undertaken, as is an examination of predicted rates with those measured in the laboratory as part of this research. A summary is provided in Section 7.4.

7.2 MODEL

The results presented in Chapter 6 provide information on weathering (by physical processes) over a simulated period of 5 years for three rock types, two air (freezer) temperature regimes and three moisture levels and these are summarised in Table 7.1.

Table 7.1: Summary of temperature and moisture conditions explored as part of this research

Air (freezer) temperature	**Season**	**Moisture Levels**		
		No moisture	**Half saturation**	**Full saturation**
+ 5 ^{O}C to -1.5 ^{O}C	***Summer***	√	√	√
+ 1 ^{O}C to – 8 ^{O}C	***Spring/Autumn***	√	√	√

The Latitudinal Gradient Project is interested in the total weathering response at each of the different locations along the Victoria Land Coast, in particular how these might be affected by future climate change. The temperature cycles and moisture levels in Table 7.1 can be used as proxy measures of climate change so that an examination of the differences in weathering, as determined by the laboratory samples, between the two temperature regimes and the three moisture levels can inform what may happen as a result of future shifts in temperature and precipitation.

Under current climate conditions, 5 years of weathering (as measured by the proportional change in weight of the granitic blocks during the laboratory simulations) at the three coastal locations is given in Figure 7.1. A simple polynomial has been fitted between the data points for each moisture level, where y is the proportional weight loss and x latitude. For each moisture level Gneiss Point experienced the least weathering and Terra Nova Bay the most, but the effect of the individual moisture levels was different for each location because of differences in rock characteristics (Chapter 6). However, it should be noted that, with the exception of Terra Nova Bay, these differences are within experimental variability.

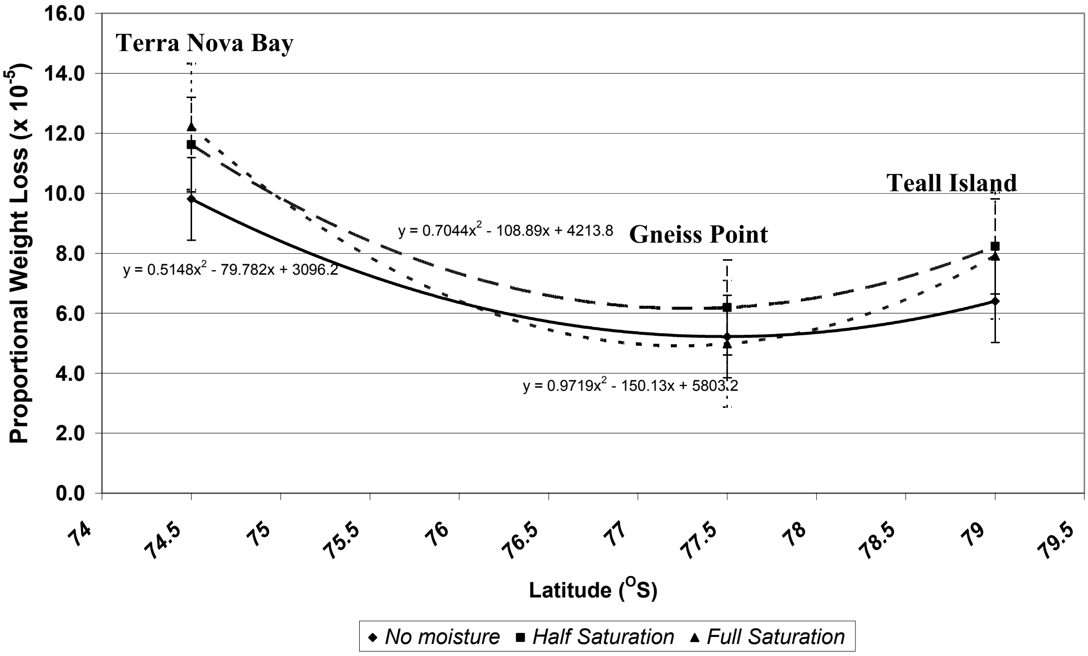


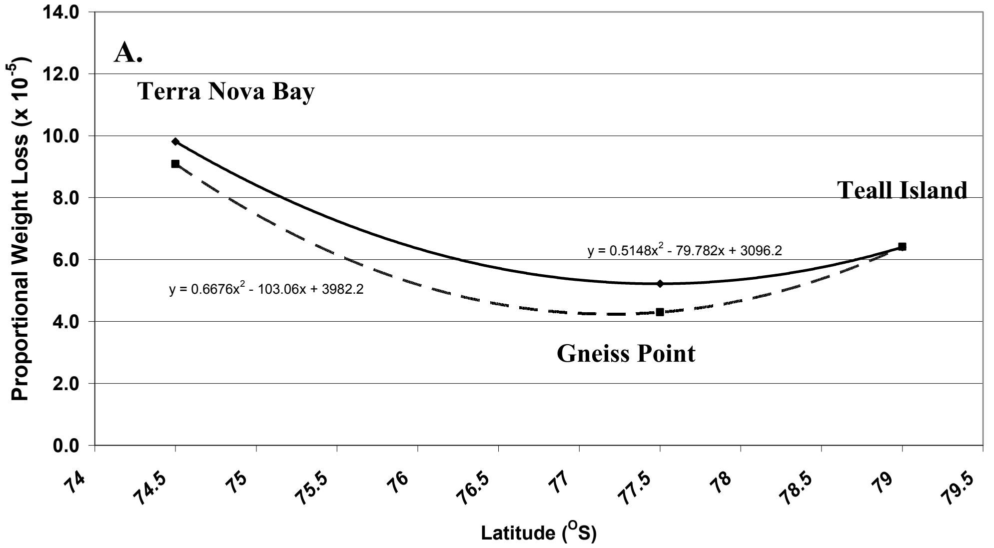
Figure 7.1: Proportional weight loss (x 10^{-5}) by moisture level and rock type under current climate conditions. Error bars are ± 1 S.E. from the mean

These differences in the impact of the summer and spring/autumn temperature cycles on weathering mean that any change in the number of these cycles as a result of climate change could have a different effect depending on rock type and moisture level (Table 6.28). Winter rock temperatures were so much lower than either the summer or spring/autumn temperatures (-20 to -30 ^{O}C; Table 5.2), that even though this is when most change is anticipated (Callaghan et al., 1999), it is very unlikely that any change in air temperature would affect the number of these cycles. Consequently, the total number of summer and spring/autumn temperature cycles would remain the same. However, the ratio between them could change with increasing air temperatures. A climate scenario where there was a change in temperature sufficient to produce a 10% increase in the number of summer cycles (and a corresponding 10% decrease in spring/autumn cycles) but no change in moisture availability is given in Table 7.2.

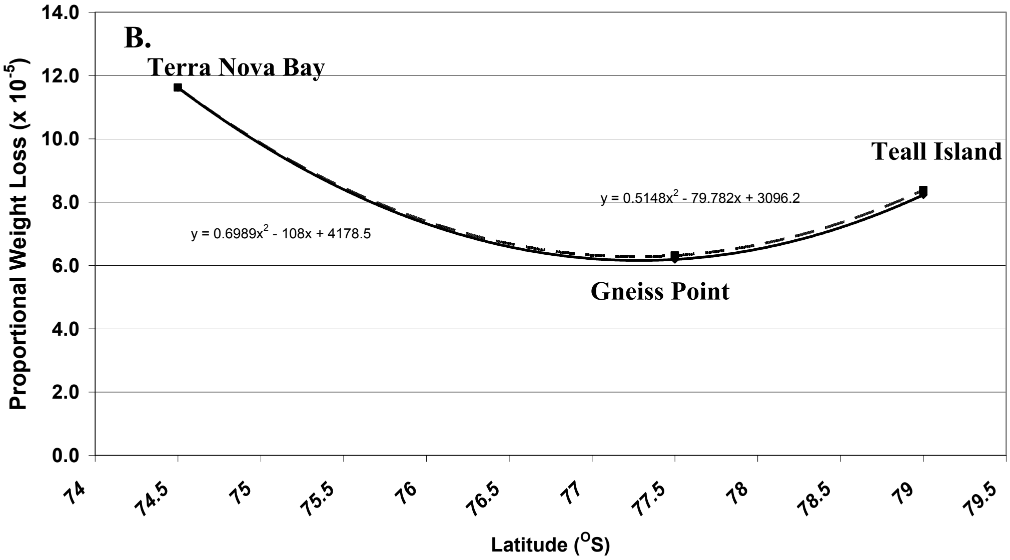
At the individual moisture levels the only real changes were at Gneiss Point and Terra Nova Bay where there would be a significant *decrease* in weathering in very dry conditions (Figure 7.2A). This was because of the much greater influence of the spring/autumn cycles on weathering rate (Table 6.28). Otherwise there would be little change regardless of moisture level (Figures 7.2 B & C). Therefore, this indicates that a change in air temperature rather than moisture availability would have the most impact on weathering.

Table 7.2: Predicted change in weathering following a 10% increase in summer temperature cycles

Location	**Proportional Change in Weight (x 10^{-5})**					
	No Moisture		**Half Saturation**		**Full Saturation**	
	Current	**After 10% increase in summer cycles**	**Current**	**After 10% increase in summer cycles**	**Current**	**After 10% increase in summer cycles**
Terra Nova Bay	9.8	9.1	11.6	11.6	12.2	12.0
Gneiss Point	5.2	4.3	6.2	6.3	5.0	5.2
Teall Island	6.4	6.4	8.2	8.4	7.9	7.8



A.
Terra Nova Bay
Teall Island
Gneiss Point
y = 0.5148x^2 - 79.782x + 3096.2
y = 0.6676x^2 - 103.06x + 3982.2
Proportional Weight Loss (x 10^-5)
Latitude (°S)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
74
74.5
75
75.5
76
76.5
77
77.5
78
78.5
79
79.5



B.
Terra Nova Bay
Teall Island
Gneiss Point
y = 0.5148x^2 - 79.782x + 3096.2
y = 0.6989x^2 - 108x + 4178.5
Proportional Weight Loss (x 10^-5)
Latitude (°S)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
74
74.5
75
75.5
76
76.5
77
77.5
78
78.5
79
79.5

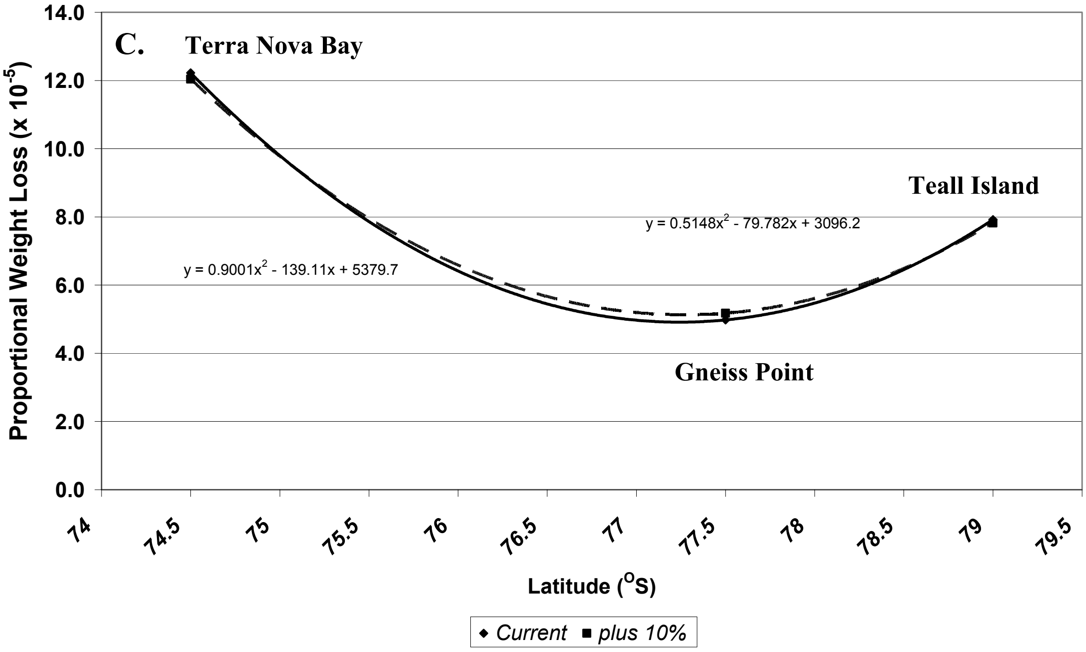


Figure 7.2: Change in weathering following a 10% increase in summer temperature cycles, A. no moisture, B. half saturation, C. full saturation

With the exception of Terra Nova Bay, the half saturation moisture level had the greatest total weathering followed by the full saturation moisture level (Figure 7.1). The decrease in weathering as a result of an increase in the number of summer temperature cycles for the no moisture samples at Gneiss Point and Terra Nova Bay produced a much clearer delineation in the effect of the moisture levels (Figure 7.2A). However, it would require a 25% increase in summer rock temperature cycles before the half saturation samples began to overtake the fully saturated samples at Terra Nova Bay (Figure 7.3).

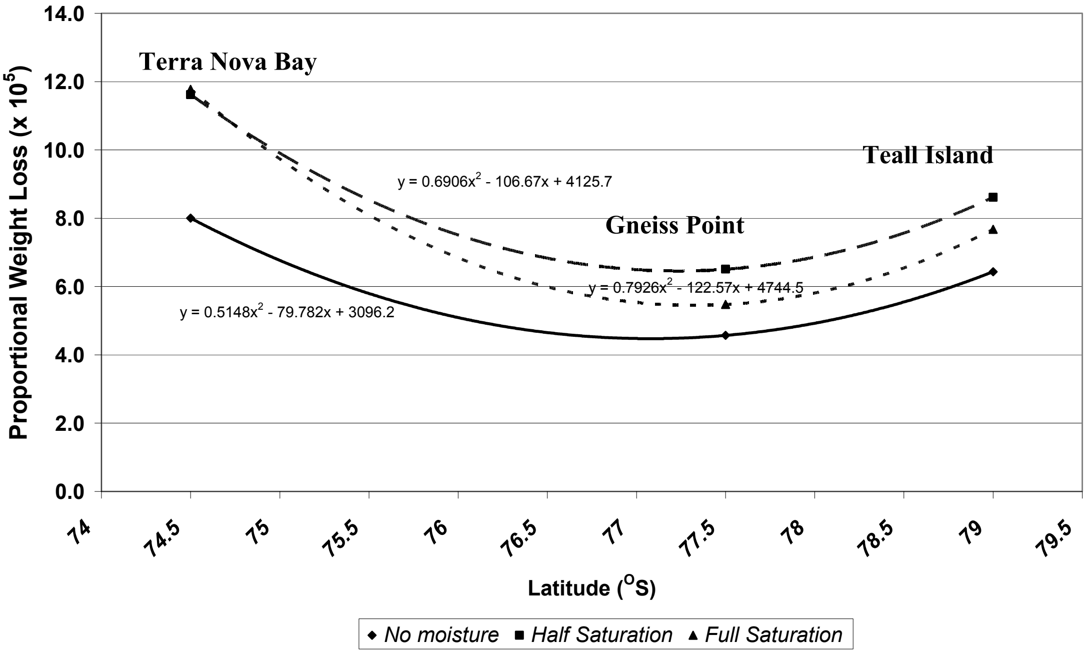


Figure 7.3: Predicted change in weathering following a 25% increase in summer temperature cycles

7.3 WEATHERING INDEX

The results of the laboratory simulations showed that rock characteristics, even within the same rock group, played a significant role in determining the rate of weathering and these must be taken into account when considering weathering rates at each of the locations. Consequently, information on individual rock characteristics as well as local climate is required before predictions can be made for other locations. A number of rock weathering classification systems that might have been used for this purpose have been developed. These range from those based on visual inspection only to those requiring a detailed suite of laboratory tests (Beavis, 1985). The ones most generally used by engineers are a combination of visual inspection together with a small number of relatively simple tests, especially those that can be conducted in the field (e.g. Irfan & Dearman, 1978). Selby (1980) developed a rock mass strength classification specifically for geomorphologists that used the strength of intact rock, the state of weathering of the rock, a variety of joint characteristics and the movement of water out of the rock mass. However, these attempts at classifying weathered rocks or determining indices of weathering have tended to focus on the current state and characteristics of the rock itself rather than on providing a predictor of how easily weathered they might be. Beavis (1985) noted that one of the most common pitfalls in using these weathering classifications was applying a classification developed for one particular rock to others, even within the same rock group.

Matsuoka (1990b) developed a predictive model for the rate of bedrock weathering by frost action based on the effective freeze-thaw frequency at the rock surface, the degree of saturation and the tensile strength of the rock mass. However, there was considerable scatter in the results and he attributed these to the variability of site characteristics, the potential effect of the definition of an effective freeze-thaw cycle and the influence of other rock properties. He later tested this model in four different environments (including Antarctica) and concluded that the model worked reasonably well in those environments where weathering was predominantly due to frost shattering and where there was a degree of saturation greater than 50%. However, he did not attempt to control for rock type differences and the model was tested on a variety of sandstones, shales and gneiss (Matsuoka, 1991). In addition, this model only took into consideration weathering by frost action but the complexity of the rock weathering system has been repeatedly stressed (e.g. Goudie, 2000; Warke, 2001) and weathering has been determined to be the result of local climate conditions, the characteristics of the rock itself and time (Section 2.2).

Hill and Rosenbaum (1998) developed an approach which fitted well within the rock weathering system developed as part of this research (Figure 2.7), involving eight significant factors that took this complexity into account. These were: climate, biological activity, mineralogy, texture, discontinuities, permeability, geomorphology (slope angle, aspect and altitude) and time. They then used the concepts of interaction matrices and fuzzy set theory to develop a weathering index. Expert knowledge of the local environmental conditions and rock type under consideration was used to assess the relative importance of the interactions between the significant factors. The weight of each interaction was determined on a scale of 0 to 4: from no interaction to critical interaction and a value assigned to each. The sum of the interaction values for each factor was then calculated (Factor Activity).

A measure for each significant factor was developed; for example, the ratio of precipitation to evaporation for climate, and fuzzy set theory used to assign a value (termed Factor Value) between 0 and 1 to each measure. Fuzzy set theory is useful in situations where the boundaries between categories may be gradational or indistinct and enables the likelihood (or probability) of a factor being significant to be taken into account. The final weathering index was the sum of the products of Factor Activity and Factor Values.

An adaptation of the approach used by Hill and Rosenbaum (1998) was used to develop a weathering index for the research sites under investigation here. Each index was built up of contributions related to a number of controlling factors where each contribution was a combination of a suitable measure for a controlling factor, the Factor Activity and the Factor Value or fuzzy set membership value. An interaction matrix, based on knowledge of the environment being investigated, was developed (Table 7.3). The Factor Activity values are the sum of the row and column totals (last row in Table 7.4) for each factor, expressed as a percentage of the total, for the matrix. For example, the Factor Activity value for mineralogy is 20 (row total) + 1 (column total) = 21, which is then expressed as a percentage of the total (e.g. 21/144 = 14.6% for mineralogy).

Table 7.3: Interaction Matrix for Field Based Weathering Index

									Row Totals	**Factor Activity**
Climate (moisture)	1	4	0	0	1	0	0	0	*6*	**12**
0	Climate (thermal)	1	0	0	0	1	1	0	*3*	**11**
0	0	Biological	0	0	0	0	0	0	*0*	**9**
0	3	0	Mineralogy	4	4	4	3	2	*20*	**21**
0	3	1	1	Texture	4	3	3	1	*16*	**20**
0	1	0	0	0	Discontinuities	4	3	1	*9*	**22**
0	0	0	0	0	2	Permeability	1	0	*3*	**16**
3	0	0	0	0	1	1	Geomorphology	1	*6*	**19**
3	0	3	0	0	1	0	2	Time	*9*	**14**
6	*8*	*9*	*1*	*4*	*13*	*13*	*13*	*5*	*72*	***144***

The next step was to identify a suitable measure for each factor and determine a fuzzy set value (Factor Value). Hill and Rosenbaum (1998) recommended a particular measure for each factor but some of these have been substituted here with more relevant and appropriate measures specific to this research. Sorptivity was used as a measure of permeability and two measures were used to represent climate: one to reflect moisture conditions and the other the thermal characteristics of the particular rock. The proportion of time the surface of the rock was wetted (as measured in the field) was used for the former and thermal conductivity for the latter. In addition, the measure used by Hill and Rosenbaum (1998) for mineralogy was orientated more towards chemical weathering so the combined proportion of quartz and biotite in the rocks under investigation here was substituted as being more indicative of physical weathering. Biological activity was evident at some of the field sites but has been excluded from the calculations because it was not expected that these processes would have any significant effect under the time scales being investigated here. In addition, the time factor was based on the age of the rocks, not on exposure date, all of which are geologically similar and so had no material effect. Table 7.5 lists the factors, the measures used to calculate them and how the fuzzy set value was estimated for each of the three rock types.

This provided the information necessary to determine the individual contributions of the different factors (Table 7.4). For example, the permeability contribution for Terra Nova Bay was the product of Factor Activity (%) and the Factor Value i.e. 16/144 x 100 (Table 7.3) x 0.048 (Table 7.4) = 0.5 (Table 7.5). The overall result, based on these indicated that most weathering would occur at Terra Nova Bay followed by Gneiss Point and then Teall Island (i.e., a north to south trend). However, this was contradictory to the results of the laboratory simulations which indicated that weathering was most at Terra Nova Bay, then Teall Island and then Gneiss Point (Figure 7.1).

Table 7.4: Controlling factor measures and Fuzzy set values

Factor	Measure and means of Estimating Fuzzy Set Value	Fuzzy Set Value		
		Terra Nova Bay	Gneiss Point	Teall Island
Climate: moisture	Proportion of summer rock surface wetted hours as measured in the field. Based on Teall Island hours = 0.1	0.39	0.17	0.10
Climate: thermal	Actual thermal conductivity where basalt = 1.95 is 1 and quartzite = 4.55 is 0	0.7	0.4	0.6
Biological	Percentage vegetation cover	0	0	0
Mineralogy	Proportion of quartz and biotite as determined by modal analysis	0.51	0.50	0.38
Texture	Based on grain size and Figure 10 in Hill & Rosenbaum (1998)	0.20	0.15	0.20
Discontinuities	RQD value for granite from Hill & Rosenbaum (1998) Figure 11	0.05	0.05	0.05
Permeability	Actual sorptivity based on Teall Island = 0.1	0.048	0.005	0.100
Geomorphology	Calculation combining slope, altitude and aspect as per Hill & Rosenbaum (1998) using actual values measured in the field	0.72	0.86	0.35
Time	Age of rocks and Figure 14 in Hill & Rosenbaum (1998)	1.0	1.0	1.0

Table 7.5: Calculation of weathering index for field conditions based on Hill & Rosenbaum (1998), circle indicates calculation described in text

Factor	**Contribution to the Index Field Estimates**		
	Terra Nova Bay	**Gneiss Point**	**Teall Island**
Climate (moisture)	3.3	1.4	0.8
Climate (thermal)	5.3	3.1	4.6
Biological	0.0	0.0	0.0
Mineralogy	7.4	7.3	5.5
Texture	2.8	2.1	2.8
Discontinuities	0.8	0.8	0.8
Permeability	0.5	0.1	1.1
Geomorphology	9.5	11.3	4.6
Time	9.7	9.7	9.7
TOTAL	***39.3***	***35.7***	***30.0***

Consequently, indices were recalculated based on those factors that would be used in a laboratory simulation. All rock types were subjected to the same time and moisture conditions and there would be no biological activity taking place in the laboratory so these factors were excluded. In addition, the nature of the specially prepared rock blocks meant that the influence of discontinuities and geomorphology could also be excluded. However, there were differences in micro-cracking between the rocks and this was included as a substitute for discontinuities. A recalculation of the weathering indices on this basis was produced which now reflected the hierarchy determined by the laboratory simulations (Table 7.7). This confirmed that even when laboratory simulations are designed to replicate field conditions as closely as possible they can be misleading, primarily because local environmental conditions such as geomorphology and age of rock are excluded.

Table 7.6: Calculation of weathering index for laboratory conditions based on Hill & Rosenbaum (1998)

Factor	**Laboratory**		
	Terra Nova Bay	**Gneiss Point**	**Teall Island**
Climate (thermal)	9.6	5.5	8.3
Mineralogy	10.8	10.6	8.1
Texture	3.8	2.8	3.8
Discontinuities	5.5	2.8	5.5
Permeability	0.9	0.1	1.9
TOTAL	**30.6**	**21.8**	**27.5**

7.4 SUMMARY

A model that related weathering rate (as measured by proportional weight loss over a simulated 5 year period of weathering) to latitude was developed for two temperature scenarios and three different moisture levels: no moisture, half saturation and full saturation. Whilst weathering was greatest at Terra Nova Bay and least at Gneiss Point at each moisture level, the effect of the summer and spring/autumn temperature cycles was different for each rock type and moisture level. These ranged from a ratio of 6.6 times more weathering following the spring/autumn cycles for no moisture at Terra Nova Bay to less than half at Gneiss Point for the full saturation moisture level (Table 7.2). These differences meant that a shift in the ratio of summer to spring/autumn temperature cycles following a change in climate would have different effects on the different environments. Only the no moisture results would be significantly affected by a 10% increase in summer cycles so that weathering would actually decrease at both Gneiss Point and Terra Nova Bay but remain the same at Teall Island if this kind of change occurred in response to rising air temperatures. In addition, changes in moisture within these values would be unlikely to see increased weathering indicating that a change in temperature would be more significant than a change in precipitation. These results were contrary to what might have been expected i.e. an increase in weathering in response to warmer, wetter conditions, and indicated that the already fragile ecosystems of the Victoria Land Coast could be placed in an even more vulnerable position following climate change.

However, the individual characteristics of the rock have been shown to affect the amount and type of weathering (Chapter 6) and so it is a combination of local climate and rock properties that are needed before a model could be used to predict weathering change at other locations. A weathering index, based on the work of Hill & Rosenbaum (1998), was developed that related a range of significant rock and climate factors to weathering. Using field values this index indicated that the Teall Island rocks would be stronger than the Gneiss Point rocks whereas the laboratory simulations had indicated that the Gneiss Point rock was the strongest. A re-calculation of the index using laboratory values identified the same hierarchy of weathering as had been found in this study. More trials are required but these results indicate that even when efforts are made to replicate field conditions in laboratory simulations, local environmental factors can still influence the outcome.

CHAPTER 8

SUMMARY

8.1 INTRODUCTION

This chapter summarises the main points from the research including Background (8.2); Field Results (8.3); Rock Characteristics (8.4); Laboratory Results (8.5) and the Model (8.6). The key findings in relation to the literature on cold climate weathering, the limitations of the research as well as potential future areas of research and papers are included in Chapter 9.

8.2 BACKGROUND

- Rock weathering is a complex, dynamic and multi-factorial process that is best described in terms of time, the inputs, processes and outputs of a process-response system
- A variety of characteristics affect the strength of granite: porosity, grain size and shape, quartz content, presence of micro-cracks and their geometry
- There is no clear consensus on which weathering process might be most effective in cold climates but there is recognition than more than one may operate and that processes may act synergistically
- Weathering rate can be expressed as a function of the individual processes that operate
- Moisture and freezing rates are important aspects of frost weathering as well as other processes
- Different processes may produce different types of weathering response
- Laboratory simulations should be conducted using micro-climatic data and replicate field conditions as closely as possible, although the use of small intact samples in simulations can affect the results

8.3 Field Results

The key results from the fieldwork are summarised below. However, there were two particular results that were contrary to expectations:

- Moisture, in the form of blowing snow, was available to wet the surface of the rock more often than had previously been supposed, even during times of negative rock temperatures and the surface could be wetted up to 40% of the time. However, the frequency, duration, timing and quantity varied with location, aspect and time of year. The presence of surface moisture means that a number of processes that had been deemed to either not operate or to operate in only very supportive environments were possible
- Winter rock temperatures were much more variable than had been anticipated and could fluctuate by up to 25 ^{O}C over a period of two weeks. They were affected by both macro-climate as well as fluctuations in air temperature following foehn and katabatic winds

Other results

- Rock surface temperatures were variable and affected by local climate conditions, aspect, season and time of day
- Rates of temperature change conducive to thermal shock were recorded at the surface but the number varied with location of thermocouple, aspect and season
- The number of freeze-thaw events varied by approximately a factor of two depending on aspect and definition of a freeze-thaw event
- Subsurface temperatures also fluctuated but there was decreasing amplitude with depth and a time lag to 90 mm depth was evident
- Subsurface moisture varied with time of day, depth and local weather conditions such as cloud or wind
- On the basis of the field investigations and the requirements of the different processes, the most likely processes to operate in these environments were

thermal shock, thermal fatigue and wetting and drying, although frost weathering by ice segregation and salt weathering should not be discounted

8.4 Rock Characteristics

Despite choosing one rock group for the investigation the individual rocks indicated a number of differences including: grain size, porosity, albedo, chemistry and mineralogy, especially proportions of quartz and feldspar, and clays were present in some of the rock samples

- The Terra Nova Bay and Gneiss Point rocks had similar quartz and biotite contents, chemical composition and albedo whereas Terra Nova Bay and Teall Island had similar grain size and extent of micro-cracking
- Thermal characteristics such as thermal conductivity and diffusivity were also different with the Gneiss Point rocks having much higher values than the Teall Island rocks, which were similar
- Moisture parameters varied with rock type so that the Terra Nova Bay and Teall Island rocks absorbed much more moisture, more rapidly than the others
- The rate at which the rocks took up moisture was affected by the cold, particularly for Teall Island and Gneiss Point where the rate of take up was reduced by approximately a factor of 2

8.5 Laboratory Results

In line with recommended practice laboratory simulations were carried out as closely as possible to field conditions and rock temperatures were used to drive the temperature cycling. Two temperature regimes and three moisture levels were investigated and weathering effects determined by changes in weight, effective porosity and ultrasonic velocity. These enabled the potential effects of frost weathering, thermal fatigue and wetting and drying in the presence of temperature fluctuations to be studied.

Of **particular interest to cold climate weathering studies** were the results that:

- Humidity fluctuations alone, in the absence of additional moisture, could produce granular disintegration and the temperature cycles did not need to cross the zero degree isotherm
- High levels of moisture were not required for weathering to occur following across zero temperature cycling and the most effective granular disintegration took place in those samples that were half saturated
- Temperature cycling above and below zero (i.e., without the necessity of crossing the zero degree isotherm), in conjunction with additional moisture could produce weathering

These are discussed more fully, and their implications for cold climate weathering research explored, in Chapter 9.

General results were:

- Small but statistically significant weight loss occurred in the rock blocks for all rock types and all moisture levels when the cumulative effect of the temperature cycles was taken into account
- There was a statistically significant temperature cycle effect for all rock types on weight loss but a moisture effect was only detected for Gneiss Point
- Proportional weight loss varied with rock type, moisture level and the type of temperature cycle and the greatest proportional weight loss in the rock blocks was not necessarily associated with the highest moisture level
- Effective porosity decreased, increased or experienced no change when the final values were compared to the initial ones. However, the different temperature cycles had different effects so that an initial decrease in effective porosity could be followed by a subsequent increase
- Where a statistically significant change occurred, ultrasonic velocity increased at the end of the experiment, but only when additional moisture had been applied

- Each rock type responded differently to the experiment with some experiencing granular disintegration only whilst others had associated changes to pore space and/or micro-cracking
- There was a statistically significant moisture effect for the aggregates following the above zero cycles for both Terra Nova Bay and Gneiss Point but this was significant for Gneiss Point only following the across zero cycles
- The weight loss of the no moisture aggregates was always less than that expected by sieving alone, regardless of temperature cycle

Results for Research Question 1: *For a specific rock group what is the total weathering rate at each of the field sites?*

- The Terra Nova Bay rocks experienced the greatest proportional weight loss followed by Teall Island and then Gneiss Point for each moisture level, although moisture levels had different effects so that maximum loss occurred in the full saturation samples at Terra Nova Bay but for the half saturation samples at Gneiss Point and Teall Island
- As well as granular disintegration, increases and decreases in void space occurred but these differed with rock type and moisture level. Increases were attributed to micro-cracking but decreases were attributed to pore blockage, internal micro-crack reconfiguration or possibly the contamination of samples by moisture
- Micro-cracking occurred in the lower levels of moisture in those rocks with larger grain size and that were previously extensively micro-cracked. Void reduction occurred in those rocks with similar mineral and chemical composition but only when additional moisture had been applied
- Estimates of weathering rates measured in the laboratory in this experiment were of a similar order to those found by Summerfield et al. (1999) for the Dry Valleys. Field rates may be even slower (Bland & Rolls, 1998)

Results for Research Question 2: *What processes are operating in this environment and what are the weathering rates for specific processes?*

- Contrary to expectations, frost weathering following 354 crossings of the zero degree isotherm was most effective in the half saturation samples, regardless of rock type and there was some evidence to support the involvement of ice segregation
- Thermal fatigue was most effective in the Terra Nova Bay rocks and temperature cycling resulted in granular disintegration or granular disintegration plus micro-cracking in the rocks with larger grain size and susceptibility to micro-cracking and these factors were found to be more important than the thermal properties of the rocks
- Wetting and drying resulted in granular disintegration or granular disintegration with an increase in void space in those rocks that had high values of sorptivity and moisture penetration but granular disintegration, and a decrease in void space in those rocks with low sorptivity and penetration
- The additional effects of wetting and drying over thermal fatigue alone were mixed, with some rocks experiencing an increase in granular disintegration, some a decrease as well as either compaction or an increase in void space
- Consideration of the cumulative effects of the two temperature cycles masked the effects of individual cycles so that these needed to be considered separately
- Estimates of weathering rates for individual processes indicated that thermal fatigue was the most effective process for the Terra Nova Bay samples and wetting and drying in conjunction with thermal fatigue for the Gneiss Point samples. Frost weathering was the most effective process for the Teall Island samples. Thermal fatigue at Terra Nova Bay was the most effective process overall

Results for Research Question 3: *Are there temperature and/or moisture regimes for which physical weathering is most effective?*

- The three moisture levels produced different responses in the rock depending on their characteristics. Whilst all (except Terra Nova Bay no moisture) experienced granular disintegration, a variety of other effects were measured, including increases in void space due to micro-cracking and/or flushing out of materials, and decreases in void space as a result of some sort of void blockage.
- No clear pattern emerged but below zero cycling produced an increase in void space in 5 out of 6 cases. Across zero temperature cycling resulted in granular disintegration, granular disintegration plus a decrease in void space or granular disintegration together with an increase in void space

8.1.5 MODEL

Research question 4 asked "*Is there a unique relationship between weathering rate and latitude, as determined by moisture and temperature conditions, along the Victoria Land Coast?*" This was addressed by developing a model that considered the effects on weathering at each of three locations under two temperature and three moisture regimes. In addition, because different rock characteristics, even for rocks from within the same rock group, were determined to affect weathering rate, a weathering index relating climate and rock properties was developed.

- Weathering, as determined by proportional weight loss, was greatest at Terra Nova Bay, followed by Teall Island and then Gneiss Point regardless of moisture level and was consistent with the calculated weathering index using laboratory parameters and with the general strength characteristics of the rocks
- When the weathering index was calculated using field data, including parameters that reflected the climate at the surface of the rock, the order of susceptibility to weathering was : Terra Nova Bay, Gneiss Point and then Teall Island, indicating that even when field data are used to determine laboratory simulations local environmental conditions could still influence the outcome

- The effect of summer and spring/autumn temperature cycles was different for each rock type and moisture level so that spring/autumn cycles could have up to 6.6 times greater effect than summer cycles but less than half in other instances
- These differences meant that a projected 10% increase in the number of summer temperature cycles as a result of climate change produced different effects at the three locations; at Terra Nova Bay and Gneiss Point there was a decrease in weathering but at Teall Island there was little change
- The implications from the experiment are that the already fragile ecosystems of the ice-free areas of the Victoria Land coast would be more vulnerable under a scenario of climate change and that it would be changes in air temperature rather than moisture that would have most effect

CHAPTER 9

KEY FINDINGS, LIMITATIONS AND POTENTIAL FUTURE RESEARCH

9.1 INTRODUCTION

Chapter 8 provides, in dot point form, all the main findings from the research. Section 9.2 highlights the five most significant findings and discusses these in the context of the current state of knowledge. Some of the more relevant and important limitations to the research are also raised. A fuller list of limitations is given in Section 9.3 and Section 9.4 highlights some of the areas identified for future research and potential papers.

9.2 KEY FINDINGS

9.2.1 CHANGING THE TEMPERATURE REGIME WAS MORE IMPORTANT THAN MOISTURE LEVEL IN AFFECTING WEATHERING RATES UNDER FUTURE SCENARIOS OF CLIMATE CHANGE

A 10% increase in summer (+5 ^{O}C to – 1.5 ^{O}C) air (freezer) temperature cycles and a corresponding 10% decrease in spring/autumn cycles (+1 ^{O}C to – 8 ^{O}C) reduced the amount of weathering (as determined by proportional weight loss of the rock blocks) at Terra Nova Bay and Gneiss Point but not at Teall Island for the samples where no additional moisture had been added. There was little measurable change in any of the samples that had been subjected to half or full saturation during the experiment under this scenario (Figure 7.1). The changes noted at Terra Nova Bay and Gneiss Point were due to the increase in weathering produced by the spring/autumn cycles (+1 ^{O}C to – 8 ^{O}C) compared to the summer cycles (+5 ^{O}C to – 1.5 ^{O}C): a factor of 6.6 and 3.0 at Terra Nova Bay and Gneiss Point respectively (Table 6.29). In other words, a future change in climate where summer temperatures rose sufficiently to increase the number of freeze-thaw cycles by 10% would, as determined by the conditions of this experiment, see a decrease in the amount of weathering at Terra Nova Bay and Gneiss Point.

However, the rocks themselves experienced different temperature cycling under the two air (freezer) temperature regimes (Table 9.1). During the spring/autumn temperature regime the Terra Nova Bay and Teall Island samples cycled within the temperature range (-4 ^{O}C to -15 ^{O}C depending on pre-existing crack length) deemed most effective for the weathering of granite rocks according to the ice segregation theory (Walder & Hallet, 1985, 1986) whilst the Gneiss Point rocks cycled across the range deemed most effective for volumetric expansion to occur.

Table 9.1: Air (freezer) and rock temperatures for the two experimental temperature cycles

Season	**Ambient air (freezer) temperature (^{O}C)**	**Rock Temperature (^{O}C)**		
		Terra Nova Bay	**Gneiss Point**	**Teall Island**
Summer	+5 to -1.5	+1.5 to -3	+5.5 to +1.5	+2 to -2.5
Spring/Autumn	+1 to -8	-4 to -10	+1.5 to -4.5	-3.5 to -9

However, the segregation ice theory also requires an open system of moisture, slow freezing rates and high permeability (Section 2.6.2) but none of these conditions apply here. Although, the moisture levels used in this experiment were higher than might have been expected in the field it was the no moisture samples that experienced the greatest difference between the two temperature cycles. Freezing rates were 3-4 ^{O}C hr^{-1} compared to the 0.1 to 0.5 ^{O}C hr^{-1} deemed most effective by Walder and Hallet (1985, 1986). In addition, the Teall Island rock, which had the highest sorptivity value of all the samples even at cold temperatures (Table 4.7), showed little difference in weathering between the two temperature cycles, which is again contradictory to what might have been expected under this theory.

There were a number of limitations to the experimental set-up that might have influenced these results. Firstly, the size and nature of the rock samples were unrealistic when compared to field conditions: samples were small, regularly shaped and smooth edged. Secondly, the experiment was conducted over a relatively short period of time: an estimated 5 years of weathering. Thirdly, only two temperature scenarios were investigated and it was assumed that the winter temperatures were too low to be affected by a temperature warming that produced a 10% increase in summer cycles. Finally, the rocks themselves responded differently to the ambient air temperature so that the actual temperatures experienced by the rock blocks were different depending on type (Table 9.1). All these factors indicate that further investigation of these results is required.

9.2.2. HIGH LEVELS OF MOISTURE ARE NOT REQUIRED FOR GRANULAR DISINTEGRATION TO OCCUR IN CONJUNCTION WITH ACROSS ZERO TEMPERATURE CYCLING

Both the Gneiss Point and Teall Island samples produced significant granular disintegration without the addition of moisture in the across zero rock temperature cycles (+1.5 to -4.5 ^{O}C and +2 to -2.5 ^{O}C respectively; Tables 6.7 & 6.9). Where moisture was applied the half saturated samples produced a greater proportion of weight loss than the fully saturated ones (although, this was within the experimental variability of the samples) (Figure 6.2). Granular disintegration following across zero temperature cycling in the absence of additional moisture contradicts the findings of Prick (1997) who identified a critical degree of saturation ranging from 50 to 93% for frost weathering to occur in her limestones using the grindosonic method. Matsuoka (2001b) also discounted frost weathering in his experiment because saturation levels were low (30 to 40%). Lautridou and Ozouf (1982) determined that where total porosity was less than 6% rocks were not 'frost sensitive'.

Although Walder and Hallet (1985, 1986) argued that a critical degree of saturation was not required for frost weathering to take place their theory did also require slow rates of freezing, permeable rock and an open system of moisture, none of which occurred here. They also theorised that the most effective temperature range for frost weathering of granite was -4 to -15 ^{O}C. As noted in Section 9.2.1, freezing rates were much higher in this experiment than those suggested by Walder and Hallet (1985, 1986) and rock permeability was low (Table 4.7). The only moisture present was the ambient humidity of the freezer indicating that it was either the temperature fluctuations alone that produced the weathering or that even very small quantities of moisture could produce granular disintegration when freeze-thaw temperature oscillations are taking place.

9.2.3. ACROSS ZERO TEMPERATURE CYCLING WAS NOT REQUIRED FOR GRANULAR DISINTEGRATION TO TAKE PLACE

The Gneiss Point samples experienced significant granular disintegration when cycling above zero (+5.5 to +1.5 ^{O}C) whilst the Terra Nova Bay (-4 to -10 ^{O}C) and Teall Island (3.5 to -9 ^{O}C) samples experienced significant granular disintegration when cycling below zero

(Tables 6.12 and 6.14 respectively). Weathering took place even in the absence of additional moisture, challenging the work of Griggs (1936) who found no change in the dry samples used in his experiments when cycling above zero. This result also provides some support for the work of Dunn & Hudec (1966) and Fahey (1983) who argued that humidity fluctuations alone could cause rock breakdown, even in the absence of clays.

Granular disintegration was evident for all moisture levels at both Terra Nova Bay and Teall Island for the below zero temperature cycles. Changes in void space as determined by changes in effective porosity also occurred for all but the Terra Nova Bay fully saturated samples (Tables 6.3, 6.13 & 6.15). Again this indicated that repeated temperature cycling, even when it is below zero degrees can produce a weathering effect and that the type, magnitude and location of that effect differs depending on the characteristics of the rock. The greatest proportional weight loss for the Terra Nova Bay samples was for the below zero no moisture samples (Table 6.12), supporting the most effective temperature range for frost weathering to occur according to Walder and Hallet (1985, 1986). However, this was not the case for the more highly sorptive Teall Island rock which had its greatest proportional effect for the half saturated samples in the frost weathering experiment. Although, the theory of Walder and Hallet (1985, 1986) required high levels of saturation, Akagawa & Fukuda (1991) and Sass (2004) have shown that ice lenses can form without saturation.

Finally, Hall and André (2001, 2003) have suggested that weathering by thermal shock is a valid and perhaps more important weathering process than frost in these environments. The production of granular disintegration in the absence of across zero temperature cycles and additional moisture adds some support for these arguments. However, the rate of change of temperature during the cycling was much less than the threshold deemed responsible for thermal shock to take place (3-4 $^{O}C\ hr^{-1}$ compared to > 2 $^{O}C\ min^{-1}$; Yatsu, 1988). In addition, there is some evidence that a temperature of 70-80 ^{O}C is required for this threshold to apply (Yong & Wang, 1980). The results in this experiment indicated that it may be the repeatedness of the temperature cycling rather than any threshold change in temperature gradient that was responsible for granular disintegration. However, as noted earlier there are a number of limitations to this experiment and further investigation would be required.

9.2.4. THE SURFACE OF THE ROCKS WERE WETTED MORE OFTEN AND FOR LONGER THAN PREVIOUS ESTIMATES OF PRECIPITATION HAD INDICATED

Campbell and Claridge (1987) had estimated very low levels of precipitation for the part of Antarctica that was the focus for this research. However, primarily as a result of blowing snow, the actual surface of the rock was found to be wet up to 40% of the time (Elliott, 2004). This result links to the work of Sass (2005) who found that it was the length of time that moisture was available rather than the quantity that was most important for weathering in these environments. This has significant implications for research into rock weathering in a 'dry' environment such as Antarctica since it is the presence of moisture on the surface of the rock and the subsequent uptake of that moisture into the rock that is important for weathering studies. In addition, as part of determining the moisture characteristics of the different rocks, an experiment was conducted into how rapidly samples of each of the different rock types took up moisture under warm and cold conditions (Table 4.7). The results of this experiment indicated that the temperature of the surface of the rock was important in determining the rate at which moisture was taken up for both the Gneiss Point and Teall Island samples but not for the Terra Nova Bay or Victoria Valley ones. The actual availability of moisture to the surface of the rock and how rapidly and easily it moves into different rock types at a range of temperatures is an important future research area for rock weathering in cold, dry environments.

9.2.5. ROCK TEMPERATURES MUST BE USED IN LABORATORY EXPERIMENTS AND WINTER CYCLING MUST BE TAKEN INTO ACCOUNT

The experiment conducted here supported previous research (e.g. Douglas, 1983; Goudie, 2000) that rock temperatures rather than air temperatures must be used in laboratory simulations (Figure 3.54). However, an unexpected additional result was that rock from the same rock group experienced different temperature cycling under the same ambient air (freezer) temperatures (Table 9.1). For instance, whilst some samples were experiencing across zero cycling others were cycling above zero even though they were subjected to the same freezer temperatures. This has implications for past and future laboratory experiments, particularly where rocks of several different types have been placed in the same freezer (e.g. Nicholson & Nicholson, 2000): all rock temperatures need to be monitored in laboratory rock weathering simulations.

There were also significant fluctuations in the temperature of the rock during winter (Figure 3.55). It is not known what effect this may have on the weathering of rock but this requires further investigation and cannot be assumed to be dead time as described by Tricart (1956).

9.3 LIMITATIONS

There were a number of limitations to both the field work and the laboratory simulations as well as in the development of the model. Perhaps most significant were the relatively few field sites visited and the lack of data for all aspects and for more than one season. Aspect and other local climate conditions are known to influence the temperature and moisture conditions experienced by the rocks and these in turn have an effect on weathering. In addition, the time frame was short and caution needs to be taken when extrapolating short term laboratory simulations on small samples of intact rock to longer term field conditions and massive rock (e.g. Viles, 2001). It also proved difficult to find sites that had near identical rocks. The effects of other processes such as thermal shock, wetting and drying without temperature fluctuations, salt weathering (and there was evidence of salt at most locations) as well as biological weathering were not investigated. These and other limitations are listed below.

9.3.1 FIELDWORK

- Only one season of data was collected at each field site and so may be atypical
- More field sites are required to more accurately determine moisture and temperature characteristics of the rocks
- Ideally the moisture and temperature conditions at all four aspects should have been measured
- It was not possible to measure precipitation directly
- Although the presence of micro-cracks were noted these were not quantified and thin section analysis may be unrepresentative and gives no information on cracking at depth

9.3.2 LABWORK

- The variable response of the different rock samples to the same freezer temperature was an unexpected result and added a further complication to determining the weathering effects
- Although in line with earlier work the rates of heating and cooling used in the experiment are greater than those found in the field and this may affect individual processes differently
- The number of replications of the rock blocks and aggregates were small and resulted in some variability in the results
- Ideally a second experiment, based on different field data should be conducted
- The laboratory simulations were carried out for a simulated period of only 5 years. It would be beneficial to continue the simulation for a much longer period as this may have an impact on the results
- Sample sizes were small so that weathering on intact rock only was conducted and it was not known what the weathering effects would be on massive rock in the field
- Winter cycling has yet to be completed and this may influence the overall weathering effect
- Thermal shock, salt weathering and wetting and drying without temperature cycling were not investigated nor were the potential effects of biological activity taken into account
- The influence of aspect on the temperature and moisture regimes was not investigated in the laboratory experiment and would require additional field data to determine the appropriate temperature cycles
- Only three levels of moisture were used and was applied by soaking, although it has been demonstrated that the method of application of moisture might affect the results
- There was a possible humidity affect on the ultrasonic velocity measurements

9.3.3 MODEL

- Only three data points were available so the model could not be fully tested
- Further predictions require additional information on rock characteristics and micro-climate at the individual sites
- The sensitivity of the weathering index to other environments was not conducted

9.4 FUTURE RESEARCH AND PAPERS

A number of areas for potential future research and/or papers have been identified. These include:

- The relationship between temperature of the rock, quantity and duration of surface moisture and subsurface moisture and weathering
- Investigating the potential weathering effects of winter temperature cycling
- Investigating the effect of aspect in the laboratory simulations
- Further investigation into the relationship between surface and subsurface moisture conditions
- Analysis of the rock temperature data gathered in the field, particularly the winter temperature
- The results found here are specific to one rock group and, because of the influence of rock characteristics on the results; it is not possible to make a more general statement about other rock groups. Therefore it would be desirable to repeat the experiment for other rock groups
- Discussing the issues identified, and some of the solutions, in linking field results to laboratory simulations
- Conducting an experiment over a longer time period and additional locations, including determining any coastal/inland effects, and the model tested
- Investigating the potential effects of salt weathering and wetting and drying (without temperature cycling) as well as additional moisture levels

- Further investigation of the influence of thermal fatigue and thermal stress on weathering and the robustness of the criteria (i.e. the 2 ^{O}C min^{-1} threshold for thermal shock)
- Further analysis of the temperature effects of different rocks in the freezer
- Investigating the role of micro-cracks and micro-crack densities in the weathering of granite
- The reliability and benefit of using effective porosity and ultrasonic velocity as measures of weathering
- The robustness and potential of the weathering index in rock weathering studies

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MAPS

United States Department of the Interior Geological Survey: 1: 50,000 Topographic Series

Marble Point: 1977, S7715-E16100/0.25X1

Victoria Upper Lake Quadrangle: 1977, S7715-E16100/0.25X1

United States Department of the Interior Geological Survey: 1: 250,000 Reconnaissance Series

Carolyn Glacier: 1963, S79000-E15600/1X7

Mount Harmsworth: 1988, 78198-S1-TR-250

ACKNOWLEDGEMENTS

There are very many people and organisations I would like to thank for their help, encouragement and support throughout my studies. Firstly, to my three able supervisors: Barry Fahey, Bryan Storey and Ian Owens, who have provided unstinting support throughout my thesis, and did their best to keep me on track. Their input has been fun as well as instructive! To all the people who helped me in the field: Justin Harrison, Jordy Hendrikx, Hilary Cave, Rob McBrearty, Blake McDavitt, Mark Morrison, with a special thanks to Yvonne Cook who came twice, I couldn't have done it without you all! My appreciation also to Angelique Prick who joined me in the field for one season and taught me a great deal (as well as cooking delicious meals in the field!).

Grateful thanks also to Justin Harrison, Nick Key, Walter Gallagher, Marney Brosnan from the Department of Geography at the University of Canterbury for their help back in Christchurch, I couldn't have done it without you either! Also to the Geology Department, especially Rob Spiers, Cathy Knight and Steve Brown, many thanks for your insights into rocks. Thanks too to Landcare Research and John Hunt for developing the software to drive the freezer.

Many thanks to all the staff at Antarctica New Zealand, especially all those at Scott Base, Keith Springer and J.R. in particular. In Christchurch, Paul Woodgate and Kevin always made sure everything went smoothly and genuinely looked pleased to see you go and come back! Thanks to the Italian Antarctic Programme for their help, support and hospitality whilst at Terra Nova Bay and to the Antarctic Meteorological Space Centre at the University of Wisconsin-Madison and the McMurdo Long Term Ecological Research Project for allowing me to access and use their AWS data.

Special thanks to the University of Canterbury, the Department of Geography and Gateway Antarctica for their encouragement and support, both financial and otherwise, to undertake this research and to Wendy Lawson who started me on this path in the first place!

Finally, thanks to my colleague PhD candidate Lee Thompson, for all those coffees and discussions and unending support no matter the crisis!

APPENDIX 1

A1.1 SAMPLE PREPARATION

Samples of approximate size 10 x 5 x 5 cm were cut from large rock boulders and brushed to remove any loose particles. Each sample was clearly labelled with a permanent ink pen, and each side digitally photographed. The labelling scheme is shown in Table 5.1. Sample length, breadth and depth were measured using Vernier callipers to the nearest 0.1 mm. Three readings were taken of each side, resulting in 12 for the length, and 6 each for the breadth and depth and then averaged. These averages were subsequently used to determine the volumes for the effective porosity measurements as well as the dimensions required for the sonometer tests. Prior to the experiment commencing all samples were weighed and effective porosity measured. Sonometer readings were taken on the dry samples. Samples were dried in an oven at 60 to 65 ^{O}C prior to them being placed in the freezer that had been pre-set to the required temperature and relative humidity. Samples were then allowed to equilibrate to the ambient freezer temperature and humidity regime for a minimum of 24 hours before the experiment began. After equilibration, samples were soaked for a specific amount of time depending on the required moisture levels and returned to the freezer.

A1.2 AGGREGATE PREPARATION

Samples were prepared in line with Fahey (1983). Offcuts from the samples were crushed using a rock crusher. The material was then sieved to remove particles < 2 mm and > 25 mm. Three replicates of 200 g each were then split off and sieved to determine their particle size distribution. Three samples from the Gneiss Point batch were used as controls to determine the effect of sieving on the analysis. The samples were then oven dried and allowed to equilibrate to the ambient freezer temperature and humidity regime for a minimum of 24 hours before the experiment began. After equilibration, they were soaked for a specific amount of time depending on the required moisture levels and returned to the freezer.

A1.3 MOISTURE APPLICATION

Three levels of moisture were applied: no moisture, half saturation and full saturation. Samples that required a level of saturation were placed in a bath and covered with water either for 7 minutes (half saturation) or 1 hour (full saturation). A controlled experiment had been conducted on the Gneiss Point rocks (as being the least porous) and weighed at regular intervals to determine the length of time required to reach half and full saturation (as determined by additional weight). Moisture was applied every 3 to 4 days under atmospheric pressure to model behaviour in the real world. The same approach was used for the aggregates.

A1.4 LABORATORY TESTS

A1.4.1 Effective Porosity

Effective porosity was measured using the saturation method as recommended by the International Society for Rock Mechanics (ISRM, 1979). Samples were wiped clean, weighed with weighing apparatus accurate to 2 decimal places of a gram and immersed in water in an airtight container under vacuum. After approximately 12 hours samples were moved to ensure that any air bubbles were released. The samples were weighed after removing any excess water from the surfaces with a damp towel after a minimum period of 24 hours and then reweighed at regular intervals until weight was consistent for at least 4 hours. They were then dried in an oven at approximately 105 ^{O}C until weight was stable for at least 4 hours.

A1.4.2 Ultrasonic Velocity

Samples were oven dried and cooled to room temperature prior to readings being taken as it is known that ultrasonic velocity is sensitive to temperature and moisture (ref). Ten readings were made on the long axis and ten on the b axis and the average values calculated. The samples were always oriented in the same direction to ensure consistency.

A1.4.3 Sorptivity

Sorptivity was determined using the methods of Alexander et al. (1999). Samples were coated with a thin layer of epoxy resin on the 4 long sides with one uncoated end placed in a small basin of water and the other end open to the air. Weight was recorded every

2 minutes for the first ten minutes and then every ten minutes until 60 minutes using a weighing machine accurate to 3 decimal places of a gram. The slope of the graph of the square root of time against cumulative weight change, after ignoring the initial 2 minute reading, is the sorptivity.

A1.4.4 Penetration

Penetration was measured using the method described by Alexander et al. (1999) and which is consistent with European Standard EN 12390-8 (October 2000). Samples were subjected to water (that had been dyed with a small amount of rhodamine) under a pressure of 500 ± 50 MPa for one hour. They were then split lengthwise using a point load tester and the distance penetrated by the dyed water measured with vernier calipers.

A1.5 FIELD MEASUREMENTS

A1.5.1 Schmidt Hammer

A Proceq N type Schmidt hammer was used to measure the hardness of the rock surface. Measurements were undertaken on a grid pattern where possible with approximately 10 cm between measurements. At least 40 measurements were undertaken. All fractures, edges and any other anomalies were avoided. Notes were made following unusual characteristics of sound. Rebound value for the rock was then determined using the average of the recorded values.

A1.5.2 Ultrasonic Velocity

Ultrasonic velocity was measured using a TICO Ultrasonic Instrument with 54 kHz transducers. The connection medium was a hair gel that had a high viscosity. This had been tested against the manufacturers recommended connection medium and had been found to have no affect on the results. Measurement in the field was undertaken by the manufacturers recommended procedure for measuring surface velocity.

A1.5.3 Subsurface Moisture

Measured using the Vaisala HM44 set for measuring relative humidity of concrete. Twelve millimetre diameter holes were drilled in the rock and plastic sleeve inserted. Probes were then inserted within sleeve and sealed with rubber plugs and protector caps (Figure 3.40). Measurements commenced after allowing recommended time for equilibration; this ensured that the air at the base of the hole had the same humidity as the rock. The tip of the sensor contains a polymer film that absorbs water molecules from the air at the base of the hole which results in the dielectric constant of the polymer changing. This in turn causes the capacitance of the sensor element to change. The change of the capacitance is almost directly proportional to the change of the relative humidity in the air. The electronics in the probe measures the capacitance of the sensor and converts the reading to a humidity output signal.

A1.5.4 Surface Moisture

Measured using Unidata Wetness Sensors/Starlog Surface Moisture Detector Model 6524A. These were attached to rock surface using small bolts and ties (Figure 3.30) and connected to the CR10X datalogger.

A1.5.5 Surface temperatures

Measured using 1 mm diameter copper-constantan thermocouples attached to surface with a clear epoxy resin and where possible covered in rock flour. Holdfast 5 minute epoxy resin was used except for Terra Nova Bay in the summer of 2003/04 when EDS Permabond was tried. However, the latter had a dark grey colour and so its use was discontinued.

A1.6 EQUIPMENT

A1.6.1 Field

Datalogger: Campbell Scientific CR10X tested for use in low temperatures

PDA: Used to store datalogger programmes and download data – Palm m125 using PC connect software

Datalogger batteries: 7 Ah; 12 Ah; 40 Ah

Thermocouples: Copper-constantan 1mm diameter

Thermistor: Campbell Scientific 107

Wind generator: Ampair Pacific 100

Pyranometer: Li-Cor LI-200X, 190SZ and 200SZ

Surface moisture sensor: Starlog Surface Moisture Detector Model 6524A

Schmidt hammer: Proceq N-type Schmidt hammer

Relative humidity probe: Vaisala HM 44 set designed to measure humidity in concrete comprising HMP44 humidity and temperature probe, HMI41 indicator, plastic sleeves, protector caps and rubber plugs

Ultrasonic device: TICO Ultrasonic Instrument manufactured by Proceq and tested to ISO 9000 standards. 54 kHz transducers

Climate: Nielsen-Kellerman Kestrel 4000 Pocket Weather Tracker

GPS: Trimble GeoExplorer 3

Digital Cameras: Nikon Coolpix 5700; Canon 3000

A1.6.2 Laboratory

Datalogger: Campbell Scientific CR21X

Thermocouples: Copper-constantan 1mm diameter

Thermistor: Campbell Scientific 107

Sieves: Endecotts Ltd. Laboratory Test Sieves

Weighing Machines: Sartorius LA2000P to ISO 9001 standard accurate to 3 decimal places of a gram

Point Load Tester: Geotechnical Systems Australia Pty Ltd. Model 6500

Dye: Weak solution of Rhodamine

Ultrasonic device: TICO Ultrasonic Instrument manufactured by Proceq and tested to ISO 9000 standards. 54 kHz transducers

APPENDIX 2

```
;{CR10X} onemin; should record and output batt volt; ref temp;' 6 thermocouple temps
; 2 moisture sensors at 1 minute interals
;For location of thermocouples and moisture sensors see LOCATION TABLE
;
*Table 1 Program
 01: 10      Execution Interval (seconds)

1: Batt Voltage (P10)
 1: 1        Loc [ battvolt ]

2: If (X<=>F) (P89)
 1: 1        X Loc [ battvolt ]
 2: 4        <
 3: 9.8      F
 4: 0        Go to end of Program Table

3: Temp (107) (P11)
 1: 1        Reps
 2: 9        SE Channel
 3: 3        Excite all reps w/E3
 4: 2        Loc [ reftemp ]
 5: 1.0      Mult
 6: 0.0      Offset


4: Thermocouple Temp (SE) (P13)
 1: 6        Reps
 2: 1        2.5 mV Slow Range
 3: 1        SE Channel
 4: 1        Type T (Copper-Constantan)
 5: 2        Ref Temp (Deg. C) Loc [ reftemp ]
 6: 3        Loc [ trock_1 ]
 7: 1.0      Mult
 8: 0.0      Offset


5: AC Half Bridge (P5)
 1: 2        Reps
 2: 5        2500 mV Slow Range
 3: 7        SE Channel
 4: 11       Excite 1 plus reps
 5: 2500     mV Excitation
 6: 9        Loc [ wetness_1 ]
 7: 1.0      Mult
 8: 0.0      Offset

6: Volt (Diff) (P2)
 1: 1        Reps
 2: 15       2500 mV Fast Range
 3: 6        DIFF Channel
 4: 11       Loc [ solar ]
 5: -112.9   Mult
 6: 0.0      Offset
```

```
7:  If time is (P92)
 1: 0       Minutes (Seconds --) into a
 2: 1       Interval (same units as above)
 3: 10      Set Output Flag High (Flag 0)

8:  Real Time (P77)
 1: 220     Day,Hour/Minute (midnight = 2400)

9:  Average (P71)
 1: 11      Reps
 2: 1       Loc [ battvolt  ]

*Table 2 Program
 02: 0.0000   Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

ONEMIN.CSI, Input Locations

Addr	Name	Flags	# Reads	# Writes	Blocks
1	[battvolt]	RW--	2	1	----- ------ ---
2	[reftemp]	RW--	2	1	Start ------ ---
3	[trock_1]	RW--	1	1	Start ------ ---
4	[trock_2]	RW--	1	1	----- Member ---
5	[trock_3]	RW--	1	1	----- Member ---
6	[trock_4]	RW--	1	1	----- Member ---
7	[trock_5]	RW--	1	1	----- Member ---
8	[trock_6]	RW--	1	1	----- ------ End
9	[wetness_1]	RW--	1	1	Start ------ ---
10	[wetness_2]	RW--	1	1	----- ------ End
11	[solar]	-W--	0	1	----- ------ End
12	[________]	----	0	0	----- ------ ---
13	[________]	----	0	0	----- ------ ---
14	[________]	----	0	0	----- ------ ---
15	[________]	----	0	0	----- ------ ---
16	[________]	----	0	0	----- ------ ---
17	[________]	----	0	0	----- ------ ---
18	[________]	----	0	0	----- ------ ---
19	[________]	----	0	0	----- ------ ---
20	[________]	----	0	0	----- ------ ---
21	[________]	----	0	0	----- ------ ---
22	[________]	----	0	0	----- ------ ---
23	[________]	----	0	0	----- ------ ---
24	[________]	----	0	0	----- ------ ---
25	[________]	----	0	0	----- ------ ---
26	[________]	----	0	0	----- ------ ---
27	[________]	----	0	0	----- ------ ---
28	[________]	----	0	0	----- ------ ---

```
;{CR10X}
;{CR10X} onehour; should record and output - battvolt; reference temperature; 6 thermocouples
;2 moisture sensors but NO solar radiation at hourly intervals
;For location of thermocouples and moisture sensor see LOCATION TABLE
;
*Table 1 Program
 01: 10       Execution Interval (seconds)

1: Batt Voltage (P10)
 1: 1        Loc [ battvolt  ]

2: If (X<=>F) (P89)
 1: 1        X Loc [ battvolt  ]
 2: 4        <
 3: 9.8      F
 4: 0        Go to end of Program Table

3: Temp (107) (P11)
 1: 1        Reps
 2: 9        SE Channel
 3: 3        Excite all reps w/E3
 4: 2        Loc [ reftemp   ]
 5: 1.0      Mult
 6: 0.0      Offset

4: Thermocouple Temp (SE) (P13)
 1: 6        Reps
 2: 1        2.5 mV Slow Range
 3: 1        SE Channel
 4: 1        Type T (Copper-Constantan)
 5: 2        Ref Temp (Deg. C) Loc [ reftemp   ]
 6: 3        Loc [ trock_1   ]
 7: 1.0      Mult
 8: 0.0      Offset

5: AC Half Bridge (P5)
 1: 2        Reps
 2: 5        2500 mV Slow Range
 3: 7        SE Channel
 4: 11       Excite 1 plus reps
 5: 2500     mV Excitation
 6: 9        Loc [ wetness_1 ]
 7: 1.0      Mult
 8: 0.0      Offset

6: If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)
```

7: Real Time (P77)
1: 220 Day,Hour/Minute (midnight = 2400)

8: Average (P71)
1: 10 Reps
2: 1 Loc [battvolt]

*Table 2 Program
02: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

End Program

Addr	Name	Flags	# Reads	# Writes	Blocks
1	[battvolt]	RW--	2	1	----- ------ ---
2	[reftemp]	RW--	2	1	----- ------ ---
3	[trock_1]	RW--	1	1	Start ------ ---
4	[trock_2]	RW--	1	1	----- Member ---
5	[trock_3]	RW--	1	1	----- Member ---
6	[trock_4]	RW--	1	1	----- Member ---
7	[trock_5]	RW--	1	1	----- Member ---
8	[trock_6]	RW--	1	1	----- ------ End
9	[wetness_1]	RW--	1	1	Start ------ ---
10	[wetness_2]	RW--	1	1	----- ------ End
11	[__________]	----	0	0	----- ------ ---
12	[__________]	----	0	0	----- ------ ---
13	[__________]	----	0	0	----- ------ ---
14	[__________]	----	0	0	----- ------ ---
15	[__________]	----	0	0	----- ------ ---
16	[__________]	----	0	0	----- ------ ---
17	[__________]	----	0	0	----- ------ ---
18	[__________]	----	0	0	----- ------ ---
19	[__________]	----	0	0	----- ------ ---
20	[__________]	----	0	0	----- ------ ---
21	[__________]	----	0	0	----- ------ ---
22	[__________]	----	0	0	----- ------ ---
23	[__________]	----	0	0	----- ------ ---
24	[__________]	----	0	0	----- ------ ---
25	[__________]	----	0	0	----- ------ ---
26	[__________]	----	0	0	----- ------ ---
27	[__________]	----	0	0	----- ------ ---
28	[__________]	----	0	0	----- ------ ---

APPENDIX 3

```
;
; Program FREEZE
;
;
; ===============================================
;
;
; Written by: John Hunt/amended by CE to include 4 thermocouples; hold temp
;          when cycles finish and use thermistor for ref temp
; Date     : May 2004
; Used to:   Simulate Antarctic Freeze/Thaw patterns.
;         Measure and control temperature and humidity in a freezer
;         that cycles from min temp to max to min, a number of times. Control temps
;         are driven from rock temperature.
;
;
; Flag controls:
;          F1 OFF
;            Resets all the default settings
;          F2 ON (user set)
;            Freezer controlling temp and humidity
;          F3 ON
;            then % thru length of cycle is determined
;            set point is linear % b/t min and max temp
;          F3 OFF
;            end of cycles or error
;            freezer and light turned OFF
;          F4 Error has occurred, F3 OFF
;
;
; Error and EOP: If the rock or freezer temps are oputside limits, Flag 4 is turned on
;            and the program is terminated.
;
;
; Input needed: Set the max temp, min temp, minutes from max to min and # cycles
;           Default for abs humidity, deadband widths set in SUB 1 defaults
;
;
; To start the program: Turn Flag 2 ON and turn Flag 3 ON.
; Cycles finished when: Flag 2 is turned off
;
;
; ---------------------------------------------------
;
;
; Flag usage:
;         F1 Initialise constants (initialise if Low)
;         F2 Start cycles and controlling
;         F3 Controlling freezer (High) End of cycles (Low)
;         F4 Error has occurred (High), normal (Low)
;         F5 Cooling (max to min - High), warming (min to max - Low)
;         F6
;
;
; Control Port:
;          1 Turn freezer ON/OFF
;          2 Turn heater (light) ON/OFF
;          3 Turn dry air ON/OFF
;
;
```

```
;
; Subroutines:
;         1 Initialise settings of temp, cycle length, cycles #, humidity, bandwidths
;         2 Measure rock temperature, freezer temp and humidity, calc wv conc
;         3 Calc cabinet SP (Temp and wvconc set point) and new temp limits
;         4
;         5 Test if freezer temp broken or end of cycle, if so turn off
;         6 Control cabinet
;         7
;         8 Turn freezer and light OFF, beep
;         79 Output data
;         80 Test if end of this cycle or All cycles
;         81 Water vapour concentration over water
;         82 Water vapour concentration over ice
;         83 End of cycles so stop controlling
;
; Input channels:
;         2H SE freezer temp (107 probe, Red)
;         2L SE freezer humidity (207 probe, White)
;         5H+5L Cu Co thermocouple for rock temp
;
;         EX1 temp and humidity excitation (107/207 probe, Black)
;         Earth Purple and clear
;
; Output data:
;         1 ID 110
;         2 Freezer set temp
;         3 Rock temp
;         4 Freezer temp
;         5 Freezer relative humidity
;         6 Freezer absolute humidity (g/m^3)
;
; How it works:
;
;
;
;
;
;
;
;
;
;
;
;
;
;
;
; ------------------------------------------------------------
;

*Table 1 Program
 01: 5        Execution Interval (seconds)

1:  If Flag/Input (P91)
 1: 21      Do if Flag 1 is Low
 2: 1       Call Subroutine 1 ;          Initialise all parameters
```

```
*Table 2 Program
 02: 10      Execution Interval (seconds)
; This needs to be set to 10s to make sure the timer is correct

1: Do (P86)
 1: 2        Call Subroutine 2 ;        Measure rock + air temperature, humidity, WV conc

2: Do (P86)
 1: 79       Call Subroutine 79 ;       Output data

; F2 must be ON to control the freezer
3: If Flag/Input (P91)
 1: 22       Do if Flag 2 is Low
 2: 83       Call Subroutine 83 ;       Turn off dry air and heater - just keep freezing

4: Do (P86)
 1: 5        Call Subroutine 5 ;        Test if temp probe working, if not STOP and beep

5: Do (P86)
 1: 80       Call Subroutine 80 ;       Test if end of this cycle or ALL cycles, if ALL set F3 high

6: If Flag/Input (P91)
 1: 13       Do if Flag 3 is High
 2: 3        Call Subroutine 3 ;        Calc cabinet SP and bandwidth

7: Do (P86)
 1: 6        Call Subroutine 6 ;        Control freezer temp

8: Do (P86)
 1: 7        Call Subroutine 7 ;        Control absolute humidity


*Table 3 Subroutines

1: Beginning of Subroutine (P85) ;      ... SUB 1
 1: 1        Subroutine 1
; Initialise parameters

2: Z=F (P30)
 1: -4       F
 2: 10       Z Loc [ Tmax      ]

3: Z=F (P30)
 1: -11      F
 2: 11       Z Loc [ Tmin      ]

4: Z=F (P30)
 1: 360      F
 2: 15       Z Loc [ CycleLngt ] ; 3h * 60 min/hr to cool, same to heat

5: Z=F (P30)
 1: 6        F
 2: 16       Z Loc [ Cycles2Do ]
```

```
6:  Z=F (P30)
 1: 0       F
 2: 18      Z Loc [ CyclCnter ]

7:  Z=F (P30)
 1: 0       F
 2: 2       Z Loc [ Timer     ]

8:  Z=F (P30)
 1: 0       F
 2: 51      Z Loc [ Cab_SP    ]

9:  Z=F (P30)
 1: 4.165   F
 2: 70      Z Loc [ RHvar1    ]

10:  Z=X*F (P37)
 1: 70      X Loc [ RHvar1    ]
 2: .00001  F
 3: 70      Z Loc [ RHvar1    ]

11:  Z=F (P30)
 1: .0097   F
 2: 71      Z Loc [ RHvar2    ]

12:  Z=F (P30)
 1: 1       F
 2: 72      Z Loc [ RHvar3    ]

13:  Z=F (P30)
 1: 6       F
 2: 61      Z Loc [ AH_SP     ]

14:  Z=F (P30)
 1: .5      F
 2: 62      Z Loc [ AH_BW     ]

15:  Z=F (P30)
 1: 2       F
 2: 52      Z Loc [ Cab_BW    ]

16:  Do (P86)
 1: 22      Set Flag 2 Low ; Stop

17:  Do (P86)
 1: 23      Set Flag 3 Low ; Stop controlling

18:  Do (P86)
 1: 24      Set Flag 4 Low ; Reset error flag

19:  Do (P86)
 1: 25      Set Flag 5 Low ; Start by cooling from max (-4) to min (-11) temp
```

```
20:  Do (P86)
 1: 11       Set Flag 1 High

21:  End (P95) ;                        ... SUB 1

22:  Beginning of Subroutine (P85)
 1: 2        Subroutine 2 ;              ... SUB 2
; Measure rock+air temp, humidity and calc water vap conc


23:  Temp 107 Probe (P11)
 1: 1        Reps
 2: 5        SE Channel
 3: 3        Excite all reps w/Exchan 3
 4: 114       Loc [ RefTemp   ]
 5: 1.0      Mult
 6: 0.0      Offset

24:  Thermocouple Temp (DIFF) (P14)
 1: 4        Reps
 2: 1        5 mV Slow Range
 3: 5        DIFF Channel
 4: 1        Type T (Copper-Constantan)
 5: 114       Ref Temp (Deg. C) Loc [ RefTemp   ]
 6: 115       Loc [ Rock_Temp ]
 7: 1.0      Mult
 8: 0.0      Offset

25:  Temp 107 Probe (P11)
 1: 1        Reps
 2: 3        SE Channel
 3: 1        Excite all reps w/Exchan 1
 4: 29       Loc [ Frez_Temp ]
 5: 1.0      Mult
 6: 0.0      Offset

26:  R.H. 207 Probe (P12)
 1: 1        Reps
 2: 4        SE Channel
 3: 1        Excite all reps w/Exchan 1
 4: 29       Temperature Loc [ Frez_Temp ]
 5: 30       Loc [ Humidity  ]
 6: 1.0      Mult
 7: 0.0      Offset

27:  Do (P86)
 1: 81       Call Subroutine 81 ; Calc absolute humidity over water

28:  Do (P86)
 1: 82       Call Subroutine 82 ; Calc absolute humidity over ice

29:  Z=X (P31)
 1: 30       X Loc [ Humidity  ]
 2: 31       Z Loc [ Frez_RH   ]
```

```
30:  Z=X (P31)
 1: 45       X Loc [ AH_water  ]
 2: 32       Z Loc [ Frez_AH   ]

31:  If (X<=>F) (P89) ; If temp below zero adjust RH and wvconc to over ice
 1: 29       X Loc [ Frez_Temp ]
 2: 4        <
 3: 0        F
 4: 30       Then Do

32:  Z=X (P31)
 1: 44       X Loc [ Hum_ice   ]
 2: 31       Z Loc [ Frez_RH   ]

33:  Z=X (P31)
 1: 46       X Loc [ AH_ice    ]
 2: 32       Z Loc [ Frez_AH   ]

34:  End (P95)

35:  End (P95) ;                      ... SUB 2

36:  Beginning of Subroutine (P85)
 1: 3        Subroutine 3 ;            ... SUB 3
; Calc set point for freezer temp from mx/min and time thru cycle

37:  Z=X+F (P34)
 1: 2        X Loc [ Timer     ]
 2: .16667   F
 3: 2        Z Loc [ Timer     ] ; 10 s interval = minutes

38:  Z=X/Y (P38)
 1: 2        X Loc [ Timer     ]
 2: 15       Y Loc [ CycleLngt ]
 3: 17       Z Loc [ CyclRatio ]

39:  Z=X-Y (P35)
 1: 10       X Loc [ Tmax      ]
 2: 11       Y Loc [ Tmin      ]
 3: 12       Z Loc [ TDiff     ]

40:  Z=X*Y (P36)
 1: 12       X Loc [ TDiff     ]
 2: 17       Y Loc [ CyclRatio ]
 3: 13       Z Loc [ dT        ]

41:  If Flag/Input (P91)
 1: 15       Do if Flag 5 is High ; Cooling phase
 2: 30       Then Do
```

```
42:  Z=X+Y (P33)
 1: 11       X Loc [ Tmin      ]
 2: 13       Y Loc [ dT        ]
 3: 51       Z Loc [ Cab_SP    ]

43:  End (P95)

44:  If Flag/Input (P91)
 1: 25       Do if Flag 5 is Low ; Heating phase
 2: 30       Then Do

45:  Z=X-Y (P35)
 1: 10       X Loc [ Tmax      ]
 2: 13       Y Loc [ dT        ]
 3: 51       Z Loc [ Cab_SP    ]

46:  End (P95)

; Temp limits
47:  Z=X+Y (P33)
 1: 51       X Loc [ Cab_SP    ]
 2: 52       Y Loc [ Cab_BW    ]
 3: 53       Z Loc [ CabSPmax  ]

48:  Z=X-Y (P35)
 1: 51       X Loc [ Cab_SP    ]
 2: 52       Y Loc [ Cab_BW    ]
 3: 54       Z Loc [ CabSPmin  ]

; WVC limits

49:  Z=X+Y (P33)
 1: 61       X Loc [ AH_SP     ]
 2: 62       Y Loc [ AH_BW     ]
 3: 63       Z Loc [ AH_SPmax  ]

50:  Z=X-Y (P35)
 1: 61       X Loc [ AH_SP     ]
 2: 62       Y Loc [ AH_BW     ]
 3: 64       Z Loc [ AH_SPmin  ]

51:  End (P95) ;                     ... SUB 3


52:  Beginning of Subroutine (P85)
 1: 5       Subroutine 5 ;            ... SUB 5
; Test if temps in range, if not ERROR TRAP, terminate

53:  If (X<=>F) (P89)
 1: 29       X Loc [ Frez_Temp ]
 2: 4        <
 3: -100      F
 4: 8       Call Subroutine 8
```

```
54:  If (X<=>F) (P89)
 1: 29       X Loc [ Frez_Temp ]
 2: 3        >=
 3: 30       F
 4: 8        Call Subroutine 8

55:  If (X<=>F) (P89)
 1: 115      X Loc [ Rock_Temp ]
 2: 4        <
 3: -100     F
 4: 8        Call Subroutine 8

56:  If (X<=>F) (P89)
 1: 115      X Loc [ Rock_Temp ]
 2: 3        >=
 3: 30       F
 4: 8        Call Subroutine 8

57:  End (P95) ;                         ... SUB 5

58:  Beginning of Subroutine (P85)
 1: 6        Subroutine 6 ;              ... SUB 6
; Control freezer temperature

59:  If (X<=>Y) (P88)
 1: 115      X Loc [ Rock_Temp ]
 2: 3        >=
 3: 51       Y Loc [ Cab_SP    ] ; too warm
 4: 52       Set Port 2 Low ;    turn OFF light

60:  If (X<=>Y) (P88)
 1: 115      X Loc [ Rock_Temp ]
 2: 3        >=
 3: 53       Y Loc [ CabSPmax  ] ; too hot
 4: 41       Set Port 1 High ;   turn ON freezer

61:  If (X<=>Y) (P88)
 1: 115      X Loc [ Rock_Temp ]
 2: 4        <
 3: 51       Y Loc [ Cab_SP    ] ; too cool
 4: 51       Set Port 1 Low ;    turn OFF freezer

62:  If (X<=>Y) (P88)
 1: 115      X Loc [ Rock_Temp ]
 2: 4        <
 3: 54       Y Loc [ CabSPmin  ] ; too cold
 4: 42       Set Port 2 High ;   turn ON light

63:  End (P95) ;                         ... SUB 6

64:  Beginning of Subroutine (P85)
 1: 7        Subroutine 7 ;              ... SUB 7
; Absolute humidity control
```

```
65:  If (X<=>Y) (P88)
 1: 32      X Loc [ Frez_AH   ]
 2: 3       >=
 3: 63      Y Loc [ AH_SPmax  ] ; too wet
 4: 43      Set Port 3 High ;     turn ON dry air

66:  If (X<=>Y) (P88)
 1: 32      X Loc [ Frez_AH   ]
 2: 4       <
 3: 64      Y Loc [ AH_SPmin  ] ; too dry
 4: 53      Set Port 3 Low ;      turn OFF dry air

67:  End (P95) ;                      ... SUB 7

68:  Beginning of Subroutine (P85)
 1: 8       Subroutine 8 ;             ... SUB 8
; Turn freezer and light OFF and keep them off

69:  Do (P86)
 1: 14      Set Flag 4 High


70:  Do (P86)
 1: 83      Call Subroutine 83


71:  End (P95) ;                      ... SUB 8

72:  Beginning of Subroutine (P85)
 1: 79      Subroutine 79 ;            ... SUB 79
; Output numbers to final storage

73:  If time is (P92)
 1: 0       Minutes into a
 2: 60      Minute Interval
 3: 10      Set Output Flag High

74:  Set Active Storage Area (P80)
 1: 1       Final Storage
 2: 110     Array ID

75:  Real Time (P77)
 1: 1110    Year,Day,Hour/Minute (midnight = 0000)

76:  Average (P71)
 1: 1       Reps
 2: 51      Loc [ Cab_SP    ]

77:  Average (P71)
 1: 4       Reps
 2: 115     Loc [ Rock_Temp ]
```

```
78:  Average (P71)
 1: 1        Reps
 2: 29       Loc [ Frez_Temp ]

79:  Average (P71)
 1: 1        Reps
 2: 30       Loc [ Humidity  ]

80:  Average (P71)
 1: 1        Reps
 2: 32       Loc [ Frez_AH   ]

81:  End (P95) ;                        ... SUB 79

82:  Beginning of Subroutine (P85)
 1: 80       Subroutine 80 ;            ... SUB 80
; Check if end of cycle or all cycles completed

83:  If (X<=>F) (P89)
 1: 17       X Loc [ CyclRatio ]
 2: 3        >=
 3: 1        F
 4: 30       Then Do ; End of half of a cycle

84:  Z=F (P30)
 1: 0        F
 2: 17       Z Loc [ CyclRatio ]

85:  Z=F (P30)
 1: 0.0      F
 2: 2        Z Loc [ Timer     ]

86:  Z=X+F (P34)
 1: 18       X Loc [ CyclCnter ]
 2: 0.5      F
 3: 18       Z Loc [ CyclCnter ]

; Change direction of temperature flow
87:  If Flag/Input (P91)
 1: 15       Do if Flag 5 is High
 2: 30       Then Do

88:  Do (P86)
 1: 25       Set Flag 5 Low

89:  Else (P94)

90:  Do (P86)
 1: 15       Set Flag 5 High

91:  End (P95) ; Change the F5

92:  End (P95) ; End of 1/2 a full cycle
```

```
93:  If (X<=>Y) (P88)
 1: 18      X Loc [ CyclCnter ]
 2: 1       =
 3: 16      Y Loc [ Cycles2Do ]
 4: 22      Set Flag 2 Low

94:  End (P95) ;                        ... SUB 80

95:  Beginning of Subroutine (P85)
 1: 81      Subroutine 81 ;              ... SUB 81
; Calc water vapour concentration over water from temp + humidity

; Calc vapour pressure
96:  Z=X*F (P37)
 1: 30      X Loc [ Humidity  ]
 2: 0.01     F
 3: 38      Z Loc [ Hum_ratio ]

97:  Saturation Vapor Pressure (P56)
 1: 29      Temperature Loc [ Frez_Temp ]
 2: 39      Loc [ Sat_VP    ]

98:  Z=X*Y (P36)
 1: 38      X Loc [ Hum_ratio ]
 2: 39      Y Loc [ Sat_VP    ]
 3: 40      Z Loc [ VP_kPa    ] ; kPa

; Calc water conc (g/m^3)

99:  Z=X+F (P34)
 1: 29      X Loc [ Frez_Temp ]
 2: 273.15   F
 3: 80      Z Loc [ Scrat4    ]

100:  Z=X*F (P37)
 1: 80      X Loc [ Scrat4    ]
 2: .46151   F
 3: 80      Z Loc [ Scrat4    ]

101:  Z=X/Y (P38)
 1: 40      X Loc [ VP_kPa    ]
 2: 80      Y Loc [ Scrat4    ]
 3: 45      Z Loc [ AH_water  ]

102:  Z=X*F (P37)
 1: 45      X Loc [ AH_water  ]
 2: 1000     F
 3: 45      Z Loc [ AH_water  ]

103:  End (P95) ;                       ... SUB 81

104:  Beginning of Subroutine (P85)
 1: 82      Subroutine 82 ;              ... SUB 82
; Calc water vapour concentration over ICE from temp + humidity
```

```
; Correct RH over water to RH over ice

105:  Z=X*Y (P36)
 1: 29       X Loc [ Frez_Temp ]
 2: 29       Y Loc [ Frez_Temp ]
 3: 77       Z Loc [ Scrat1    ]

106:  Z=X*Y (P36)
 1: 77       X Loc [ Scrat1    ]
 2: 70       Y Loc [ RHvar1    ]
 3: 77       Z Loc [ Scrat1    ]

107:  Z=X*Y (P36)
 1: 71       X Loc [ RHvar2    ]
 2: 29       Y Loc [ Frez_Temp ]
 3: 78       Z Loc [ Scrat2    ]

108:  Z=X+Y (P33)
 1: 78       X Loc [ Scrat2    ]
 2: 72       Y Loc [ RHvar3    ]
 3: 78       Z Loc [ Scrat2    ]

109:  Z=X+Y (P33)
 1: 77       X Loc [ Scrat1    ]
 2: 78       Y Loc [ Scrat2    ]
 3: 79       Z Loc [ Scrat3    ]

110:  Z=X/Y (P38)
 1: 30       X Loc [ Humidity  ]
 2: 79       Y Loc [ Scrat3    ]
 3: 44       Z Loc [ Hum_ice   ]

; Calc vapour pressure
111:  Z=X*F (P37)
 1: 44       X Loc [ Hum_ice   ]
 2: 0.01     F
 3: 41       Z Loc [ Hum_ratlc ]

; Use this for vap pressure over ice
112:  Polynomial (P55)
 1: 1        Reps
 2: 39       X Loc [ Sat_VP    ]
 3: 42       F(X) Loc [ Sat_VPice ]
 4: -.00486  C0
 5: .85471   C1
 6: .2441    C2
 7: 0.0      C3
 8: 0.0      C4
 9: 0.0      C5
```

```
113:  Z=X*Y (P36)
 1: 41       X Loc [ Hum_ratIc ]
 2: 42       Y Loc [ Sat_VPice ]
 3: 43       Z Loc [ VP_kPa_ic ] ; kPa

; Calc absolute humidity over ice

114:  Z=X+F (P34)
 1: 29       X Loc [ Frez_Temp ]
 2: 273.15   F
 3: 80       Z Loc [ Scrat4    ]

115:  Z=X*F (P37)
 1: 80       X Loc [ Scrat4    ]
 2: .46151   F
 3: 80       Z Loc [ Scrat4    ]

116:  Z=X/Y (P38)
 1: 43       X Loc [ VP_kPa_ic ]
 2: 80       Y Loc [ Scrat4    ]
 3: 46       Z Loc [ AH_ice    ]

117:  Z=X*F (P37)
 1: 46       X Loc [ AH_ice    ]
 2: 1000     F
 3: 46       Z Loc [ AH_ice    ]

118:  End (P95) ;                   ... SUB 82

119:  Beginning of Subroutine (P85)
 1: 83       Subroutine 83 ;        ... SUB 83
; Keep things off either before or at end of prog 120 keeps freezer at max temp


120:  Do (P86)
 1: 6        Call Subroutine 6


121:  Do (P86)
 1: 53       Set Port 3 Low ; Turn OFF dry air

122:  Do (P86)
 1: 22       Set Flag 2 Low

123:  Do (P86)
 1: 23       Set Flag 3 Low

124:  Do (P86)
 1: 25       Set Flag 5 Low

125:  Z=F (P30)
 1: 0        F
 2: 2        Z Loc [ Timer     ]
```

```
126: Do (P86)
 1: 0       Go to end of Program Table

127: End (P95) ;                    ... SUB 83
```

End Program

Addr	Name	Flags	# Reads	# Writes	Blocks
1	[Rubbish]	----	0	0	----- ------ ---
2	[Timer]	RW--	2	4	----- ------ ---
3	[_________]	----	0	0	----- ------ ---
4	[_________]	----	0	0	----- ------ ---
5	[_________]	----	0	0	----- ------ ---
6	[_________]	----	0	0	----- ------ ---
7	[_________]	----	0	0	----- ------ ---
8	[_________]	----	0	0	----- ------ ---
9	[PanelTemp]	----	0	0	----- ------ ---
10	[Tmax]	RW--	2	1	----- ------ ---
11	[Tmin]	RW--	2	1	----- ------ ---
12	[TDiff]	RW--	2	1	----- ------ ---
13	[dT]	RW--	3	1	----- ------ ---
14	[_________]	----	0	0	----- ------ ---
15	[CycleLngt]	RW--	1	1	----- ------ ---
16	[Cycles2Do]	RW--	1	2	----- ------ ---
17	[CyclRatio]	RW--	2	2	----- ------ ---
18	[CyclCnter]	RW--	2	2	----- ------ ---
19	[_________]	----	0	0	----- ------ ---
20	[_________]	----	0	0	----- ------ ---
21	[_________]	----	0	0	----- ------ ---
22	[_________]	----	0	0	----- ------ ---
23	[_________]	----	0	0	----- ------ ---
24	[_________]	----	0	0	----- ------ ---
25	[_________]	----	0	0	----- ------ ---
26	[_________]	----	0	0	----- ------ ---
27	[_________]	----	0	0	----- ------ ---
28	[_________]	----	0	0	----- ------ ---
29	[Frez_Temp]	RW--	11	1	----- ------ ---
30	[Humidity]	RW--	4	1	----- ------ ---
31	[Frez_RH]	-W--	0	2	----- ------ ---
32	[Frez_AH]	RW--	3	2	----- ------ ---
33	[_________]	----	0	0	----- ------ ---
34	[_________]	----	0	0	----- ------ ---
35	[_________]	----	0	0	----- ------ ---
36	[_________]	----	0	0	----- ------ ---
37	[_________]	----	0	0	----- ------ ---
38	[Hum_ratio]	RW--	1	1	----- ------ ---
39	[Sat_VP]	RW--	2	1	----- ------ ---
40	[VP_kPa]	RW--	2	1	----- ------ ---
41	[Hum_ratIc]	RW--	1	1	----- ------ ---
42	[Sat_VPice]	RW--	1	1	----- ------ ---
43	[VP_kPa_ic]	RW--	2	1	----- ------ ---
44	[Hum_ice]	RW--	2	1	----- ------ ---
45	[AH_water]	RW--	2	2	----- ------ ---
46	[AH_ice]	RW--	2	2	----- ------ ---
47	[_________]	----	0	0	----- ------ ---
48	[_________]	----	0	0	----- ------ ---
49	[_________]	----	0	0	----- ------ ---
50	[_________]	----	0	0	----- ------ ---
51	[Cab_SP]	RW--	6	5	----- ------ ---
52	[Cab_BW]	RW--	2	1	----- ------ ---

53	[CabSPmax]	RW--	1	2	----- ------ ---
54	[CabSPmin]	RW--	2	2	----- ------ ---
55	[__________]	----	0	0	----- ------ ---
56	[__________]	----	0	0	----- ------ ---
57	[__________]	----	0	0	----- ------ ---
58	[__________]	----	0	0	----- ------ ---
59	[__________]	----	0	0	----- ------ ---
60	[__________]	----	0	0	----- ------ ---
61	[AH_SP]	RW--	2	1	----- ------ ---
62	[AH_BW]	RW--	2	1	----- ------ ---
63	[AH_SPmax]	RW--	1	2	----- ------ ---
64	[AH_SPmin]	RW--	2	2	----- ------ ---
65	[__________]	----	0	0	----- ------ ---
66	[__________]	----	0	0	----- ------ ---
67	[__________]	----	0	0	----- ------ ---
68	[__________]	----	0	0	----- ------ ---
69	[__________]	----	0	0	----- ------ ---
70	[RHvar1]	RW--	2	2	----- ------ ---
71	[RHvar2]	RW--	1	1	----- ------ ---
72	[RHvar3]	RW--	1	1	----- ------ ---
73	[__________]	----	0	0	----- ------ ---
74	[__________]	----	0	0	----- ------ ---
75	[__________]	----	0	0	----- ------ ---
76	[__________]	----	0	0	----- ------ ---
77	[Scrat1]	RW--	4	2	----- ------ ---
78	[Scrat2]	RW--	3	2	----- ------ ---
79	[Scrat3]	RW--	1	1	----- ------ ---
80	[Scrat4]	RW--	4	4	----- ------ ---
81	[__________]	----	0	0	----- ------ ---
82	[__________]	----	0	0	----- ------ ---
83	[__________]	----	0	0	----- ------ ---
84	[__________]	----	0	0	----- ------ ---
85	[__________]	----	0	0	----- ------ ---
86	[__________]	----	0	0	----- ------ ---
87	[__________]	----	0	0	----- ------ ---
88	[__________]	----	0	0	----- ------ ---
89	[__________]	----	0	0	----- ------ ---
90	[__________]	----	0	0	----- ------ ---
91	[__________]	----	0	0	----- ------ ---
92	[__________]	----	0	0	----- ------ ---
93	[__________]	----	0	0	----- ------ ---
94	[__________]	----	0	0	----- ------ ---
95	[__________]	----	0	0	----- ------ ---
96	[__________]	----	0	0	----- ------ ---
97	[__________]	----	0	0	----- ------ ---
98	[__________]	----	0	0	----- ------ ---
99	[__________]	----	0	0	----- ------ ---
100	[__________]	----	0	0	----- ------ ---
101	[__________]	----	0	0	----- ------ ---
102	[__________]	----	0	0	----- ------ ---
103	[__________]	----	0	0	----- ------ ---
104	[__________]	----	0	0	----- ------ ---
105	[__________]	----	0	0	----- ------ ---
106	[__________]	----	0	0	----- ------ ---

107	[__________]	----	0	0	-----	------	---
108	[__________]	----	0	0	-----	------	---
109	[__________]	----	0	0	-----	------	---
110	[__________]	----	0	0	-----	------	---
111	[__________]	----	0	0	-----	------	---
112	[__________]	R---	1	0	-----	------	---
113	[__________]	-W--	0	1	-----	------	---
114	[RefTemp]	RW--	1	1	-----	------	---
115	[Rock_Temp]	RW--	7	1	Start	------	---
116	[Rock_2]	-W--	0	1	-----	Member	---
301	[__________]	----	0	0	-----	------	---
302	[__________]	----	0	0	-----	------	---
303	[__________]	----	0	0	-----	------	---
304	[__________]	----	0	0	-----	------	---
305	[__________]	----	0	0	-----	------	---
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328	[__________]	----	0	0	-----	------	---
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370	[__________]	----	0	0	----- ------ ---
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157	[Rock_43]	-W--	0	1	----- Member ---
158	[Rock_44]	-W--	0	1	----- Member ---
159	[Rock_45]	-W--	0	1	----- Member ---
160	[Rock_46]	-W--	0	1	----- Member ---
161	[Rock_47]	-W--	0	1	----- Member ---
162	[Rock_48]	-W--	0	1	----- Member ---
163	[Rock_49]	-W--	0	1	----- Member ---
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223	[Rock_109]	-W--	0	1	----- Member ---
224	[Rock_110]	-W--	0	1	----- Member ---
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227	[Rock_113]	-W--	0	1	----- Member ---
228	[Rock_114]	-W--	0	1	----- Member ---
229	[Rock_115]	-W--	0	1	----- Member ---
230	[Rock_116]	-W--	0	1	----- Member ---
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232	[Rock_118]	-W--	0	1	----- ------ End
233	[PaRefTemp]	----	0	0	----- ------ ---

APPENDIX 4

Rock Weathering Processes in Antarctica: A Comparison of Some Recent Studies with Those from the Northern Hemisphere

CHRISTINE ELLIOTT

ABSTRACT

A review of some recent studies on rock weathering in Antarctica has revealed that Antarctic weathering research has a significant contribution to make to the ongoing debate about rock weathering in cold climates. Largely conducted in the field rather than the laboratory as in the Northern Hemisphere, it demonstrates that whilst all weathering processes can occur in Antarctica this is highly localised and dependent on the particular micro-environment. Freeze-thaw, for example, is not the most dominant process in many parts of Antarctica. The right combination of rock temperature and moisture can mean that salt, insolation, hydration or even chemical weathering can predominate.

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After considering a number of alternatives Yatsu (1988: 2) settles on Correns' (1939) definition of weathering as being "the alteration of rock minerals *in situ*, at or near the surface of the earth and under the conditions which prevail there". The use of the term *in situ* distinguishes weathering from erosion, which involves the transport of material. Goudie (1994: 556) believed weathering to be "one of the most important of geomorphological and pedological processes……..". The weathering of rock plays a fundamental role not only in shaping the landscape, but also, by providing the nutrients and materials for soil formation to begin, in terrestrial ecosystem development. It is weathering that initially breaks up the rock, or reduces it sufficiently in strength, to enable the processes of erosion to occur. In addition, it is an important component of the rock cycle.

The processes of weathering are often classified into mechanical (physical), chemical or biotic (biological) (Selby, 1993), and it is generally accepted that mechanical weathering is predominant in cold climate environments (e.g. Campbell & Claridge, 1987; Matsuoka, 1995), although some chemical (e.g. Ishimaru and Yoshikawa, 2000) and, for example as a result of fungal activity, biological (Hirsch, et al., 1995) weathering does occur. Consequently French (1996) preferred the term cryogenic weathering meaning the combination of mechanico-chemical processes, which cause the *in situ* breakdown of rock under cold climate conditions.

According to Selby (1993) the most significant factors affecting the rate of weathering are climate and the physical and chemical composition of the parent rock and the most commonly recognised physical weathering processes are:

- Internal rock stress
- Insolation
- Frost action
- Salt crystal growth
- Wetting and drying

Site factors are also important, especially the rate of soil drainage. However, rock break-up will only occur when the forces exerted are greater than the strength of the rock (Hall, 1987).

Although there is a wealth of knowledge on rock weathering from Antarctica, most cold climate studies have been undertaken in the Northern Hemisphere and have focussed on freeze-thaw in particular (Hall, 1992). Matsuoka (1995) pointed out however, that whilst frost weathering was considered dominant in humid cold regions, little was known about its efficacy in cold deserts. Consequently the purpose of this paper is to review some of the literature on rock weathering in both the Northern Hemisphere and the Antarctic, with a particular emphasis on the processes involved and their relationship to climate and rock properties. The role of freeze-thaw is especially highlighted. The key results from the Antarctic studies will be identified and any contribution that the studies in Antarctica might have to the overall debate on rock weathering in cold climates is highlighted. An improved understanding of rock weathering in Antarctica is particularly important because of the slow rates of weathering that operate there and the impacts any changes in their rate may have on the continued development of Antarctica's fragile ecosystems.

Developments in the Northern Hemisphere

Freeze-thaw

Initial theory on the freeze-thaw mechanism was based on the assumption that weathering was a result of the 9 percent expansion of water in either cracks (frost action) or between grains of rock (frost weathering) as it froze and subsequently thawed. Early experiments concluded that it was the frequency of these freeze-thaw cycles (i.e. crossings of the 0^{0} C air temperature) that caused the rock to break down (e.g. Russell, 1943). However, subsequent studies showed that these cycles could be few or even absent in cold climate environments (Fahey, 1973) and the results of other research into intensity, rate (e.g. Lautridou and Ozouf, 1982) or type of cycle (e.g. Wiman, 1963) were inconclusive and/or contradictory. Some also noted that very small amounts of debris were actually produced during these experiments (Wiman, 1963; Potts, 1970; Brockie, 1972).

Subsequently McGreevy (1981) recognised that more than one rock weathering mechanism could operate and that the nature of the rock, moisture supply and thermal conditions also needed to be considered. McGreevy and Whalley (1982) also found that air temperatures were poor indicators of rock temperatures and that laboratory experiments on small samples of 'intact' rock need not necessarily reflect what happened in the field with 'massive' rock. Fahey and Lefebure (1988), in a field experiment, identified that there were fewer freeze-thaw cycles in rock than in air and that these reduced with depth. In addition, maximum debris release closely corresponded with maximum groundwater seepage and access to moisture was found to be an important factor in other studies on freeze-thaw (e.g. Matsuoka, 1990a).

Several attempts were made to build theoretical or mathematical models (Hallet, 1983; Walder & Hallet, 1985; Tharp, 1987; Matsuoka, 1990b) and Walder and Hallet (1985) introduced the idea, as an alternative to the 9 percent volume expansion theory, that water might migrate within rock to form segregation ice. Matsuoka (1990a) confirmed that volumetric expansion was not the unique cause of frost shattering and, in his predictive model (Matsuoka, 1990b), that freeze-thaw frequency on the rock surface was a more important parameter than either degree of saturation or the tensile strength of the rock. Finally, there was growing recognition that freeze-thaw might not be the dominant mechanism in some circumstances (Boelhouwers, 1993; Hall, 1995; Halsey et al., 1998) and that interrelationships between processes might operate (Hall, 1992).

Salt weathering and freeze-thaw

Salt weathering results from stresses in rock caused by the crystallization of salts in rock pores through either the growth of crystals from solution, thermal expansion or hydration (Selby, 1993; Fahey, 1985; Goudie, 1994), although other mechanisms have also been suggested (Williams & Robinson, 1991). The salts come either from the sea or inland lakes or are derived from the chemical weathering of the rock itself (Selby, 1993) and are widely recorded throughout the Polar Regions (Williams and Robinson, 1981), including Antarctica (Evans, 1970, cited in McGreevy, 1982). However, Selby (1993) noted that magnesium sulphate ($MgSO_4$) and thenardite (Na_2SO_4) might be relatively uncommon in most inland deserts. A number of studies have cited the potential importance of salt weathering in cold environments, including Antarctica (e.g. Gore, et al., 1996, Gore and Colhoun, 1997, Rodriquez-Navarro and Doehne, 1999).

Several attempts have been made to measure the combined action of freeze-thaw and salt weathering or to make comparisons between them. Williams and Robinson (1981) for example found that the presence of salt enhanced rates of frost weathering whereas McGreevy (1982) found the opposite. Fahey (1985) put this contradiction down to the different levels of salt used in these two experiments. McGreevy (1982) also found that halite (NaCl) had greater effect than either thenardite or $MgSO_4$, whereas most others found that thenardite had greater effect (e.g. Williams and Robinson, 1981; Fahey, 1983). Fahey (1985), who also considered hydration as well as freeze-thaw and salt weathering, found that the presence of salt increased both hydration and frost weathering but that this depended on both the salt and the type of rock. He also noted that the actual amount of salt in solution in rocks was unknown. Finally, Goudie (1999) found that resistance to salt weathering was a poor predictor of resistance to frost weathering in limestone.

Hydration and insolation weathering

Whilst there have been some studies conducted on the hydration process in cold environments (Fahey, 1983; Fahey and Dagesse, 1984; Hall and Hall, 1996) the low moisture availability in some parts of Antarctica means this has not been regarded as a particularly important process there. However, Hall and Hall (1996) found that wetting and drying had an effect on the internal characteristics of the rock, which could influence the nature and degree of other weathering processes, and Fahey (1983) noted that this process operated throughout the year.

Early studies on thermal expansion and contraction found that this process was unlikely to weather rocks (Blackwelder, 1933; Griggs, 1936), although subsequent investigations did find some micro-fracturing (Aires-Barros et al., 1975, cited in Selby, 1993). Yatsu (1988) however, estimated that heating rates of greater than 2 °C per minute could produce cracking and permanent strain in rocks and that the cracks were most likely to occur along grain boundaries. Coutard & Francou (1989) also found that a granite rock surface in the French Alps experienced a 30 °C temperature range and that diurnal fluctuation was still perceptible at 48 cm depth within the rock.

Summary

In summary therefore, evidence from studies in the Northern Hemisphere that freeze-thaw or salt weathering (either acting individually or together) are effective mechanisms in rock disintegration remains inconclusive. There also continues to be a lack of clarity on how these mechanisms work with some studies noting that little debris is produced by freeze-thaw (e.g. Lautridou and Seppala, 1986; Tharp, 1987). In addition, with a few notable exceptions (e.g. Lautridou and Seppala, 1986; Fahey and Lefebure, 1988), these studies were primarily undertaken in the laboratory and on sedimentary rock, usually limestones or sandstones. Although the importance of temperature, moisture and rock properties is recognised there is no clear evidence as to which freeze-thaw cycle may be the most effective nor what type or concentration of salt. Little cognisance has been taken of insolation weathering in Northern Hemisphere rock weathering studies.

Antarctic Studies

According to Campbell and Claridge (1987), whilst physical weathering is the dominant process of rock decay in Antarctica, low moisture availability means that water based processes are not very effective there, freeze-thaw is comparatively restricted, and weathering is much less intensive than in the alpine or subalpine zones of more temperate areas. Salt weathering is stated as being the dominant process in the Dry Valleys but there is little evidence to indicate that insolation weathering was a significant mechanism in breaking up the rock (Campbell and Claridge, 1987).

Recent studies fall largely into two groups; those that have been conducted in the Maritime Antarctic and those that have been conducted in the more arid cold desert environments (Figure 1).

Maritime Antarctic

Campbell and Claridge (1987) identified the Maritime Antarctic as the west coast of the Antarctic Peninsula and the islands north of 55 °S. The temperature range is –12 °C to +12 °C with precipitation between 200 and 1000 mm per annum. The soils are moist and ground temperatures may rise above freezing for short periods in any month of the year.

Signy Island

Signy Island (Figure 1) has a cold oceanic climate with mean monthly temperature of approximately –4 °C and low precipitation (400 mm per year) and sunshine (on average 1.5 hours per day) (Hall, 1986). Geologically the island consists of metamorphosed sediments, mainly quartz-micaschist (Hall, 1986, citing Mathews and Maling, 1967).

A number of rock samples from different locations on Signy Island were tested for moisture content by Hall (1986) using a weighing technique. He found that moisture content was a major factor in rock weathering on Signy Island but that it varied over both time and space, and even within the same rock type. For example, the moisture content of samples that had been lying under snow for more than 24 hours ranged from 0.10 percent to 1.13 percent for the same rock. He also identified the saturation coefficient as the best indicator of potential frost action. However, Hall (1987) found a significant difference between the response of 'massive' rock and 'intact' rock to mechanical weathering. Massive rock is *in situ* rock that is fractured and faulted, whereas intact rock consists of small pieces of rock without such fracturing or faulting (Attewell and Farmer, 1976). In addition, field tests on small rock samples placed at various locations in the field for varying lengths of time indicated that mechanical weathering rates were very slow but varied with rock type (Hall, 1990).

Hall and Hall (1991), in a series of laboratory experiments on quartz-micaschist, reproduced temperature and insolation regimes similar to those experienced on the island. They found that, although freeze-thaw cycles induced by changes in air temperature did not produce rates of change of temperature sufficient to cause thermal stress fatigue, values of up to 7 °C min^{-1} occurred in the rock when the 'sun' was turned off. Linear regression indicated that this rate of change could penetrate to a depth of approximately 2.2 cm into the rock. However, they also pointed out that, because thermal stress fatigue and freeze-thaw operate within the same zone, it would be extremely difficult to discern the role played by either in rock breakdown.

Livingston Island

Livingston Island has a much higher level of precipitation (1000 to 1500 mm, John and Sugden, 1971) than Signy Island. The rocks are mainly volcanics interbedded with conglomerates and sandstones (Hall, 1993a citing Hobbs, 1968; Smellie et al., 1980). Wetting and drying was found to be the main weathering mechanism on the northern aspect

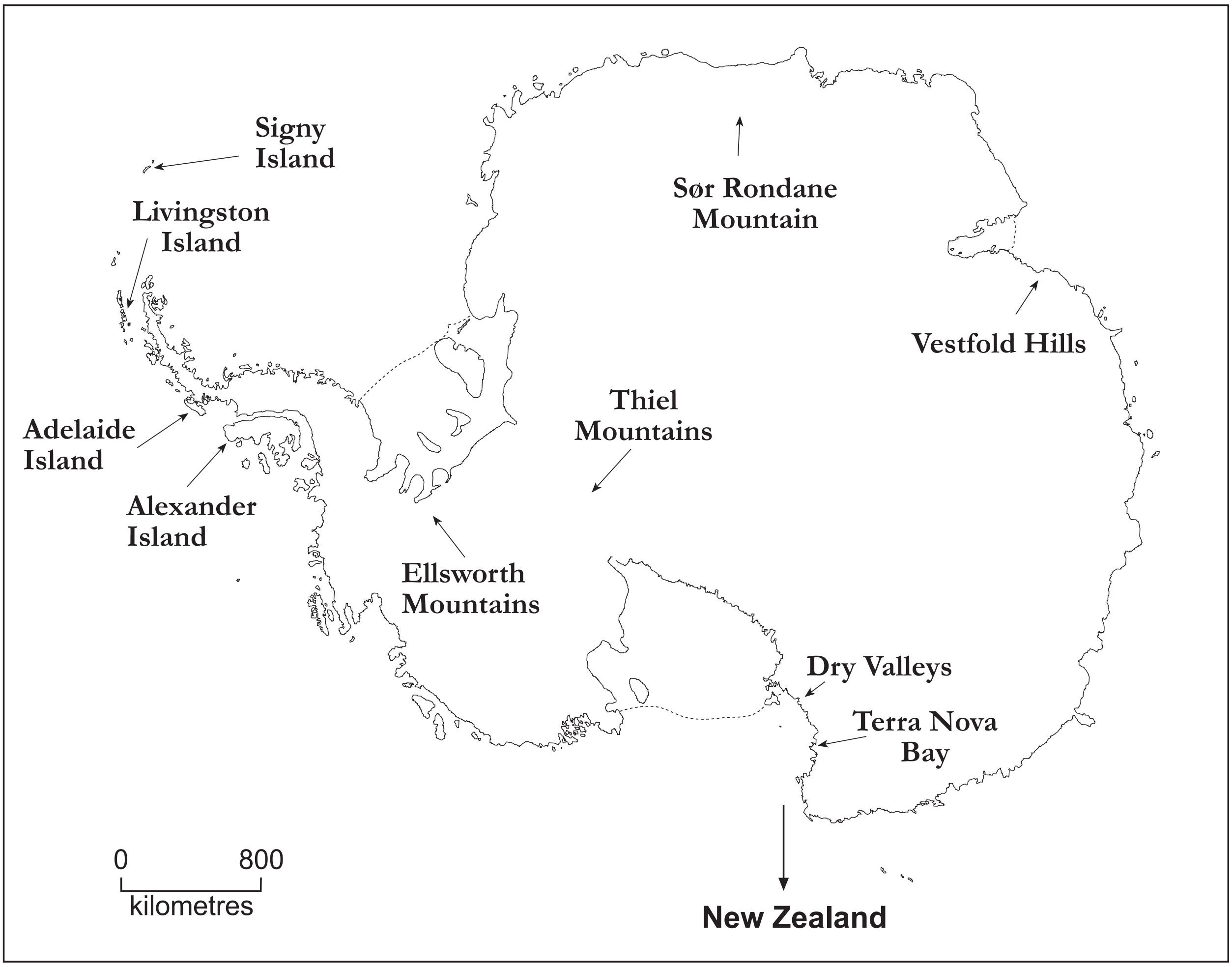

Figure 1: Sketch map of Antarctica, indicating the location of the different studies discussed in the text

of the rocks due to the dominant northerly rain-bearing winds, whilst chemical weathering was evident on southern aspects, mainly as a result of snowmelt. Freeze-thaw was not common and might only be found where the rate of freezing during winter was slow enough to enable segregation ice to develop (Hall, 1993a). Hall (1993b) used a Schmidt Hammer to test for differences in rock hardness as an indicator of differences in rock strength. He found that those parts of the rock containing snowpatches had significantly lower readings than those without and concluded that chemical weathering predominated where snowpatches were present whereas mechanical weathering was dominant when they were absent.

Alexander Island

Although Alexander Island (Figure 1) is located within the Maritime Zone, the study site in Viking Valley is described as having a cold, dry, continental type climate (Hall, 1997a). The rocks are largely sandstone, conglomerates and argillaceous sediments (Taylor et al., 1979). A series of field experiments over two winters and one summer collected data on air, surface and inner rock temperatures (Hall, 1997a, b). Freeze-thaw weathering was very limited and most effective on the western to northern aspects where more moisture was available. Although there was no evidence of chemical weathering he found that the rate of change of temperature in the rock was far greater than 2 ^{0}C per minute and concluded that thermal stress fatigue may be the dominant weathering process in this area. There was also evidence of wetting and drying and salt weathering by gypsum.

Adelaide Island

Hall (1998) measured rock temperatures on Adelaide Island (Figure 1) at one-minute intervals on both the surface and at 2 cm depth. The key result from this work was the gain in information on both freeze-thaw and thermal gradients that a one-minute data collection interval offered. For example, rates of change of temperature greater than the minimum estimated for thermal stress fatigue to occur were found in the one minute data, albeit for very short periods, but were not evident in the 15 or 30 minute data intervals.

Arid Areas

The arid areas of Antarctica can be found within the Interior Antarctic Plateau (e.g. Thiel Mountains), Inland

Mountain, Central Mountain (e.g. Sør Rondane Mountains) or Coastal Mountain Dry Valleys climatic zones of Campbell and Claridge (1987). They are characterised by large annual temperature ranges that fall to below –50 ^{0}C in the cold central core of the Antarctic Plateau, and moisture regimes of as little as 15 to 20 mm per annum.

Sør Rondane Mountains

The Sør Rondane Mountains (Figure 1) lie approximately 200 km from the coast of East Antarctica (Matsouka, 1995). Insolation is strong in summer generating frequent freeze-thaw cycles at the ground surface and the mean annual air temperature is –18.4 ^{0}C. The rocks are mainly gneiss, granite, amphibolite and diorite (Matsuoka, 1995). Observations of scaling from rock walls and the disintegration of tuff blocks that had been soaked in saline solutions and exposed to field situations were carried out over a 5-year period (Matsuoka et al., 1996). Effective freeze-thaw cycles (defined as those where the rock surface temperature rose above +2 ^{0}C after falling below –2 ^{0}C, Matsuoka, 1990b) exceeded 100 per annum. However, bedrock shattering rates (<1 %) were much lower than for areas in the Northern Hemisphere that experienced much fewer freeze-thaw frequencies (Matsuoka, 1991).

After 4 or 5 years' exposure the blocks of tuff soaked in pure water or gypsum showed little visible breakage, whereas the thenardite blocks were significantly cracked and rounded and the halite blocks were almost completely worn down. However, halite is almost absent in these mountains and gypsum most common (Matsuoka, 1995). Whilst there was some evidence of chemical weathering, insolation weathering was not deemed significant.

Terra Nova Bay

Terra Nova Bay in Northern Victoria Land (Figure 1) is located within the Coastal Antarctic climatic region as defined by Campbell and Claridge (1987). French and Guglielmin (1999) found that freeze-thaw weathering was limited despite the relatively high number of freeze-thaw cycles that occurred (50 per annum), even at 2 cm depth in the rock. Salts however, derived almost certainly from the sea, were plentiful. They concluded that traditional frost action was not the dominant process of rock disintegration but that thermal stresses and/or salt weathering may be the cause of the shattered rock and well developed tafoni and honeycomb weathering found there.

Thiel Mountains

Nolan Pillar (85^0 26'S, 86^0 46'W) is a small nunatak at about 1600 m above sea level in the south-eastern-most part of the Thiel Mountains (Figure 1) in inland Antarctica (Ishimaru and Yoshikawa, 2000). These mountains are characterised by extremely low temperatures (estimated by Ishimaru & Yoshikawa 2000, to be –36 ^{0}C, using data from Rubin, 1962) and very little water. They observed three different types of weathering, granular disintegration, micro-sheeting and rock varnish, and investigated these using optical microscopy, scanning electron microscopy and energy dispersive spectrometry. They concluded that the granular disintegration and micro-sheeting that had occurred were a result of cracking of minerals due to the differential thermal stresses between quartz and plagioclase, and that the rock varnish was a result of oxidation.

Vestfold Hills

The Vestfold Hills (Figure 1) are an ice-free area of approximately 400 km^2 on the coast of Princess Elizabeth Land. The rocks are mainly gneiss with a number of basaltic dykes protruding above the bedrock. The low albedo of the rock means that this area has a warmer climate than other areas at similar latitudes. Gore et al. (1996) and Gore and Colhoun (1997) investigated the composition, distribution and origin of surficial salts in this area and discussed the relationship between these and distinctive regional contrasts in weathering, which were independent of bedrock. They found that the region to the west of the 'salt line' contained marine-derived salts that were aggressive agents of rock weathering whereas the area to the east of this line was characterised by salts formed from chemical weathering of the substrates.

Ellsworth Mountains

The Ellsworth Mountains (Figure 1) are located within the Inland Mountain Zone of Campbell and Claridge (1987) and are typified by low temperatures and precipitation. Yoshikawa et al. (2000) undertook a series of measurements of both surface and subsurface temperatures of black marble. They also measured the moisture content of several small blocks of marble and tuff left in the field. Moisture to the rock surface was supplied mostly by snow blown by katabatic winds rather than precipitation. Little accumulation of debris and few effective freeze-thaw cycles (as defined by Matsuoka, 1990b) were observed between January 1992 and January 1993. Consequently, frost weathering was regarded as relatively inactive and moisture conditions deemed to control the weathering process. However, they did also conclude that freeze-thaw was more effective than salt weathering, although there was no discussion or explanation for this conclusion given in the paper.

Dry Valleys

The Dry Valleys of Antarctica is an area of very low moisture, cold winter temperatures and warm enough in summer for air temperatures to rise above freezing (Campbell and Claridge, 1987). Several studies have been conducted in the Dry Valleys (Taylor, Wright and Victoria) of South Victoria Land (Figure 1). Johnston (1972) investigated both salt weathering and freeze-thaw in the Taylor Valley and concluded that the particular mechanism that dominated depended on the micro-environment. Where sodium chloride (NaCl) was present, salt weathering was the predominant mechanism but where this was absent, and there was evidence of increased moisture, freeze-thaw became more important. He found evidence of only very small amounts of chemical weathering taking place.

Conca and Astor (1987) studied cavernous weathering on dolerites at Bull Pass in the Victoria Valley. They modelled the flow of moisture through joint blocks and investigated the influence that differences in permeability at the surface, as a result of chemical weathering, had on this flow. Pore water was deflected away from those areas with lower permeability and a graphical representation of the flow through these rocks had a close resemblance to their resulting morphology.

Miotke (1982) discussed physical weathering in the Taylor Valley in some detail. He recorded a series of rock temperatures in order to explain these physical weathering processes. He found that, whereas micro-climate played an important role in both frost shattering and thermal stress fatigue, it was differential evaporation caused by differences in temperature within the rock that initiated salt weathering. In addition, high summer temperatures (above 0 °C) encourage chemical weathering. He concluded that, in order to understand rock weathering processes better, further investigations of short-term variations in micro-environments were needed. In a subsequent paper Miotke and von Hodenberg (1983) studied salt fretting and chemical weathering in the Darwin Mountains as well as the Dry Valleys. They investigated both the occurrence of salts as well as potential sources of moisture. They concluded that the processes of chemical weathering in Antarctica were the same as those elsewhere and that it was the physical environment that determined which one operated rather than geographical location. A short summary paper (Miotke, 1988) gave a good overview of these studies and included some discussion on the potential role of biological weathering, which is seen to be minor but not to be ignored.

Key results from the Antarctic studies

Table 1 summarises the key parameters such as climate and rock type as well as the approach, process or processes and outcomes of these studies. Overall the research conducted in the Antarctic concluded that freeze-thaw, if important at all, is highly localised. For example, Hall (1997a, b) found that in the Viking Valley on Alexander Island, whilst there were sufficient temperature oscillations to produce freeze-thaw, lack of moisture meant it only occurred in the more moist western and northern aspects. Similarly, Matsuoka et al. (1996) put the low rates of bedrock shattering within the Sør Rondane Mountains down to the low moisture content of the rock (30-40 %) rather than to any shortage of freeze-thaw cycles. On Livingston Island, however, whilst the moisture was sufficient for freeze-thaw to occur, rock temperatures rarely fell below 0 °C and so again freeze-thaw was very localised (Hall, 1993a).

Other effects of micro-climate or micro-environment were also evident. For example, the insulation provided by snow could either prevent the thermal conditions necessary for freeze-thaw from occurring or slow down the cooling rate sufficiently to allow water migration and hence segregation ice and freeze-thaw to occur (Hall, 1993a). Chemical weathering was greatly enhanced by the presence of snowpatches (Hall, 1993b; Ishimaru and Yoshikawa, 2000). Even in arid areas wetting and drying could also be present, (Hall 1997a, b) and salt weathering was deemed to play a major role in the Sør Rondane Mountains (Matsuoka et al., 1996) and the Dry Valleys (Johnston, 1972; Miotke, 1982) but not in the Thiel Mountains (Ishimaru and Yoshikawa, 2000).

The potential role of insolation weathering was stressed in several studies (e.g. Hall, 1998; Hall and Hall, 1991; French and Guglielmin, 1999) and in others cited as the predominant mechanism (e.g. Hall 1997a, b; Ishimaru and Yoshikawa, 2000). The lack of mention of insolation weathering in the Northern Hemisphere literature was put down to other processes such as freeze-thaw or hydrolysis concealing it in the more temperate environments (Ishimaru and Yoshikawa, 2000). Hall (1997b) found that data collected at one minute intervals identified rates of temperature change in rock that were greater than that required for thermal stress fatigue to occur.

The type of rock and its properties were also highlighted (Hall, 1986; Matsuoka, 1995). For instance, the location and concentration of quartz within a quartz-micaschist affected not only its strength but also its moisture content and hence potential vulnerability to frost action (Hall, 1986). He also found that moisture content varied over both time and space and even within the same rock type. Ishimaru and Yoshikawa (2000) observed that the rates of thermal expansion and the thermal conductivity for the quartz and plagioclase of the Nolan Pillar were very different and hence encouraged insolation weathering.

Hall (1992) stressed that processes worked synergistically and used earlier work done on Signy Island to develop a series of flow charts detailing the different processes, their inter-relationships and the factors that controlled them. Each flow chart, for example freeze-thaw (page 109), included decision points, based on field and simulated data, to help identify the actual mechanisms involved. He concluded that an element that controlled one process (e.g. temperature change for freeze-thaw) could also exert an influence on others (e.g. thermal stress fatigue) and therefore the conditions that facilitated freeze-thaw weathering could also enable other processes such as wetting and drying, salt and/or thermal fatigue to occur.

Several studies identified some points of importance for laboratory experiments. For example Hall (1986) found that laboratory simulations sometimes exaggerated actual moisture contents and Matsuoka et al. (1996) suggested that the dominance of rock breakdown due to halite rather than thenardite in their field experiment was a result of the different temperature and humidity conditions used in the

Table 1: Summary of more recent rock weathering research in Antarctica

Location	Climate	Rock Type	Approach	Process	Main Points	Source
Signy Island Latitude: 60° 43'S Longitude: 45° 38'W	Cold, oceanic, mean monthly temperature -4°C, precipitation 400 mm/yr. (mainly snow), sunshine c. 1.5 hrs/day, average wind speed 26 km/hr (Hall, 1986, citing Watson, 1975)	Quartz-micaschist	Examined moisture content of rock samples in the laboratory and in the field.	Freeze-thaw	Moisture content varied over time and space.	Hall (1986)
			Field studies using a Schmidt Hammer to estimate rock strength.	Freeze-thaw	Found a significant difference between the response of 'massive' rock to 'intact' rock in the field. Moisture content major factor in rock weathering in that particular environment.	Hall (1987)
			Small rock samples placed at various locations in the field and for varying lengths of time.	Freeze-thaw	Mechanical weathering rates very slow, approximately 2% loss in mass of samples per 100 years, with marble having greater rates than the quartz-micaschist.	Hall (1990)
			Laboratory simulated temperature and insolation regimes.	Insolation weathering	Rate of change of air temperatures insufficient to cause thermal stress fatigue. However, rate of change of temperature in the rock itself is sufficient. Temperature fluctuations recorded to 22 mm depth in the rock.	Hall & Hall (1991)
Livingston Island Latitude: 62° 40'S Longitude: 61° 00'W	Mean annual temperature -3°C, annual precipitation 1000 to 1500 mm (John & Sugden, 1971)	Diorite	Field and laboratory investigating rock moisture content.	Freeze-thaw, Wetting & drying, Chemical weathering	Freeze-thaw not so ubiquitous as previously thought. Wetting and drying, salt and chemical weathering all play major roles depending on micro-climatic characteristics of site.	Hall (1993a)
		Dolerite Basalt	Use of Schmidt Hammer in the field.	Freeze-thaw; Chemical weathering	Weathering enhanced on lee side of outcrop as a result of prolonged wetting by melting snow.	Hall (1993b)
Alexander Island Latitude: 71° 50'S Longitude: 68° 21'W Altitude: 300 m a.s.l.	Mean summer temperature -2.5°C, mean winter temperature -11.5°C.	Sandstone	Field including the use of ultrasonic test and Schmidt Hammer.	Freeze-thaw, Insolation weathering	Concludes that insolation weathering may be dominant process here.	Hall (1997a,b)
Adelaide Island Latitude: 67° 34'S Longitude: 61° 07'W Altitude: 50 m a.s.l.		Granodiorite	Measured rock temperatures at surface and at 22 mm depth.	Insolation weathering	Important to measure temperatures at 1 minute intervals or less to identify temperature gradients sufficient for insolation weathering to occur.	Hall (1998)

Table 1 (cont.): Summary of more recent rock weathering research in Antarctica

Location	Climate	Rock Type	Approach	Process	Main Points	Source
Sør Rondane Mountains Latitude: 72°S Longitude: 22.5°E. 200km. from the coast. Altitude: 3000 m a.s.l.	Mean annual air temperature -18.4°C ESE katabatic winds at average speeds of 12.6m per second	Tuff	Observation of scaling from rock walls. Small rock samples soaked in saline solutions and exposed to field conditions for 5 years.	Freeze-thaw, Salt weathering	Freeze-thaw cycle defined to occur when the rock surface temperature crosses + or - 2°C. Weathering rates low compared to northern hemisphere. Freeze-thaw very localised and salt weathering the dominant mechanism.	Matsuoka (1995); Matsuoka et al., (1996)
Terra Nova Bay Latitude: 74° 42'S Longitude: 164° 05'W Altitude: 90 m a.s.l.	Mean air temperature - 14.7°C. Mean annual precipitation (snow) probably <200mm (citing Bull, 1971) Strong and persistent katabatic winds.	Granite	Field observations.	Freeze-thaw, Salt weathering Insolation weathering	Freeze-thaw limited but salts plentiful. Concludes that thermal stress fatigue or salt weathering are the dominant processes.	French & Guglielmin (1999)
Thiel Mountains Latitude: 85° 26'S Longitude: 86° 46'W Altitude: 1600 m a.s.l.	Annual mean air temperature -36°C. Annual precipitation 100 mm (Rubin, 1962)	Granodiorite porphyry	Thin sections analysis; X-ray diffraction, Energy Dispersive Spectrometry, Scanning Electron Microscopy.	Insolation weathering, Chemical weathering	Granular disintegration and micro-sheeting a result of cracking of minerals due to differential thermal stresses of constituents. Chemical weathering also evident.	Ishimaru & Yoshikawa (2000)
Vestfold Hills Latitude: 68° 33'S Longitude: 78° 15'W Altitude: 30-100 m a.s.l.	Mean Annual temperature -10.2 °C. Mean annual wind speed 5 ms-^{1}, generally from the E. Snow falls 8 - 16 days per month (Campbell & Claridge, 1987)		X-ray diffraction; Electron probe analysis.	Salt weathering Chemical weathering	Identified distinctive morphology and salt types east and west of a 'salt line'. Distinguished between marine derived salts and those produced by weathering.	Gore et al., (1996); Gore & Colhoun, (1997)
Ellsworth Mountains Latitude: 80° 21'S Longitude: 81° 35'W Altitude: 1250-1400 m a.s.l	Mean Annual Air temperature -17.3 °C. Katabatic winds from SE dominate (Yoshikawa et al., 2000). Mean Annual Precipitation 250 mm (Campbell & Claridge, 1987)	Black Marble Tuff	Field measurements of surface and subsurface rock temperatures. Moisture content of small rock blocks.	Freeze-thaw	Weathering processes dominated by frost action. Most important control on frost shattering was moisture availability.	Yoshikawa et al. (2000)
Dry Valleys Latitude: 76°30'-78°30'S Longitude: 160-166°E Altitude: 90-2000m a.s.l.	Mean Annual Temperature -20 °C. Mean annual precipitation 45 mm. (Campbell & Claridge, 1987)	Granite	X-ray powder diffraction.	Salt weathering Freeze-thaw Chemical weathering	Weathering mainly due to physical processes. Which dominates depends on micro-environment.	Johnston (1972)
		Dolerite	Modelling.		Modelling flow of water through joint blocks indicates how tafoni formed.	Conca & Astor (1987)
		Marble Dolerite	Field measurements of surface and subsurface rock temperatures.	Physical weathering	The process that operates depends on the micro-environment.	Miotke (1982)
		Dolerite	X-ray diffraction.	Salt weathering Chemical weathering	Chemical weathering processes same as elsewhere, dominant process depends on physical factors rather than geographical location.	Miotke & von Hodenberg (1983)
		Dolerite		All	Notes potential role of biological weathering.	Miotke (1988)

laboratory experiments. Hall (1987) found that the strength of quartz-micaschist depended on both the location of the quartz inclusions and whether the load was applied parallel or normal to schistosity. He also noted that, even if the moisture levels used by Lautridou and Ozouf (1982) in their laboratory experiments were available on Signy Island, temperatures there rarely fell below –8 ^{0}C on other than a seasonal basis and hence the 500 cycles used in their experiments significantly exaggerated this real field situation.

With a few exceptions (e.g. Lautridou and Seppala, 1986; Fahey and Lefebure, 1988, Matsuoka et al., 1997) the Northern Hemisphere studies were conducted on sedimentary rocks and in the laboratory. The Antarctic studies on the other hand were conducted on a wide range of rocks, for example volcanics interbedded with conglomerates and sandstones (Hall, 1993a); quartz-micaschist (Hall, 1986, 1987); dolerite (Hall, 1993a) and tuff (Matsuoka et al., 1996), and usually in the field, either on the actual rocks themselves (e.g. Hall, 1997a, b; Matsuoka et al., 1996) or on rock blocks exposed to the local environment (e.g. Hall, 1986, 1993) or by field inspections (e.g. French and Guglielmin, 1999).

Conclusion

The studies undertaken within Antarctica on rock weathering processes and mechanisms contain a wealth of information, primarily from fieldwork, on rock properties, temperatures and gradients as well as moisture. This work has clearly identified the crucial role of the micro-environment in determining which weathering process or processes operate and how effective they are in producing rock breakdown. In the Northern Hemisphere on the other hand studies have been largely conducted in laboratory conditions and on a relatively restricted set of sedimentary rocks. Several important implications for these laboratory studies have also been highlighted by the work in Antarctica.

Freeze-thaw is, in many cases, not recognised as being the predominant mechanism in Antarctica but rather one that operates only in very localised environments where the right combination of rock temperatures and moistures occur. Even where one mechanism may be found to dominate (e.g. Hall 1997a, b), a number of others were found to operate at the same time and in close proximity. The potential role of insolation weathering is also stressed. Unfortunately there appears to be little evidence that research in the Northern Hemisphere recognises the contribution that the Antarctic studies can make to the better understanding of rock weathering in cold climates, and yet future advances in this understanding may well occur in Antarctica where the emphasis is on field work rather than laboratory studies.

Some areas for future research have been highlighted, for instance despite the clear recognition of the role of moisture in cold climate weathering, little work has been undertaken to quantify such a role. The critical levels of moisture required for each of the different processes to operate have not been established nor have moisture gradients within the rock itself been investigated in the field. Whilst it has also been established that more than one process might operate in any particular environment the relationship between these processes has not been determined.

Acknowledgments

My appreciation to Gateway Antarctica for the opportunity to participate in the Graduate Certificate course and to Barry Fahey for his continuing advice, support and encouragement in my studies.

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Surface Moisture Availability and Rock Weathering in Cold Climates

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ABSTRACT

The importance of moisture in determining which rock weathering processes may operate, as well as the rate at which rock weathering occurs, has long been recognised. However, little is known about how often or when moisture is available to the rock surface, or for how long the surface may be wetted. This paper gives some initial results from current research on granite rocks in Antarctica. Recordings of surface moisture, for two aspects and three locations in Victoria Land, show that moisture reaches the rock surface more frequently than might initially have been expected in this dry climate. The number of occasions the surface is wetted, and the quantity of moisture the surface received, varied with aspect and time of year. Rock surfaces could be wet for up to 40% of the time during the summer months. This has important implications for rock weathering where some processes are deemed not to operate, or to operate in very restricted locations, due to the apparent absence of moisture.

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Introduction

Water, according to Rahn (1996), is a "peculiar mineral": first, because it exists in three natural states or phases (solid, liquid, vapour). Second, it is more dense as a liquid than a solid, with maximum density at +4 ^{O}C and third, it expands by 9 percent on freezing. Finally, water also has some high thermal characteristics, for example a specific heat[1] of 4.18 x 10^3 J kg^{-1} K^{-1}, approximately four times that of air. Bland and Rolls (1998) note that these properties, together with its wide distribution, mean that water plays a dominant role in most weathering processes, acting either as a solvent, an active component in a chemical reaction or as the source of a physical force. Recently, Hall et al. (2002), in a review of weathering in cold regions, stressed the importance of moisture in influencing the processes that operate (physical, chemical or biological) and went so far as to state that it is moisture availability, not temperature, that limits weathering, including chemical weathering, in these regions.

An additional property of water that is important for weathering studies in cold climates is that, depending on the amount of solutes present and pore size, water will freeze at temperatures below 0 ^{O}C, and this temperature may differ for different rocks (Douglas et al., 1983). Water can also continue to exist as a liquid in small quantities even at very low temperatures. For example, Hall (1988) found that unfrozen water could exist to as low as –18 ^{O}C in the mica-schists of Signy Island, Antarctica.

Whilst a number of studies have recognised the importance of moisture[2] in rock weathering research (e.g. Odegard and Sollid, 1993), few have investigated this in any detail. Field studies have largely concentrated on how spatial and temporal variability in access to water influences either the weathering processes that operate (e.g. Hall, 1993a) or when most weathering occurred (e.g. Fahey and Lefebure, 1988). Some laboratory studies have tried to identify critical levels of moisture or a moisture-related property of the rock that can be used to determine weathering rates (e.g. Matsuoka, 1991; Prick, 1997), others have investigated specific processes involving moisture such as hydration shattering (e.g. Fahey and Dagesse, 1984) or how water migrates in rocks (e.g. Prick, 1995).

However, few studies have investigated how often or for how long the surface of a rock becomes wetted in cold, dry climates such as those found in Victoria Land, Antarctica

(Figure 1). The results presented here attempt to fill some of this gap in knowledge about the availability of moisture for rock weathering. Although the focus of this paper is on the availability of moisture to the surface of the rock it is recognised that these results form only a small component of the overall picture on rock weathering in cold climates. Data on surface and subsurface rock temperatures as well as subsurface moisture regimes are in preparation. In addition, the influence of moisture on the rate of some weathering processes as determined in the laboratory is being investigated.

Study approach

Sites

Data were collected from three locations in Victoria Land, Antarctica: two coastal (Terra Nova Bay and Gneiss Point) and one inland (Victoria Valley) (Figure 1). The coastal locations provide a latitudinal gradient of approximately 2.5 degrees, whilst Victoria Valley and Gneiss Point provide a coastal/inland perspective. Gneiss Point (77° 24’S, 163° 42’E; altitude 50 m) and Victoria Valley (77° 23’S, 161° 55’E; altitude 400 m) were investigated during the summer of 2002/03 and Terra Nova Bay (74° 41’S, 164° 07’E; altitude 100 m) in the 2003/04 season. Equipment constraints meant that only two aspects were investigated at each location: south and west for the coastal locations and north and a horizontal surface at the inland one. The south and west aspects were chosen for the coastal sites as being the most likely to provide contrasting moisture and temperature regimes.

Rock type

In an attempt to reduce the potential influence of rock type variation on the experimental results a single rock type (Granite Harbour Intrusives) was chosen for the study. X-Ray Diffraction (XRD) analysis of samples from Gneiss Point and Victoria Valley indicate that unweathered rock is composed of 50 to 55 percent quartz; the remainder being mainly feldspar together with a small quantity of biotite. Weathering rinds were clearly evident in the samples from both Gneiss Point and Victoria Valley and the XRD analysis identified traces of clay minerals (although the specific minerals are not known) in some of those from the latter.

An examination of some characteristics of the rocks at each location indicated that there were some differences. For instance, the size of the feldspar crystals at Terra Nova Bay was up to an order of magnitude larger than those at the other locations but the albedo was somewhat lower. Rock hardness, a proxy for rock strength, was estimated in the field using a Schmidt Hammer and varied with both aspect and location. The potential effects of these differences on rates of weathering will be examined in the laboratory.

Instrumentation

Surface moisture was measured using a sensor that detects the presence of rainfall, dew, fog or snow and was recorded between October/November and January during each season. The sensor consists of a continuous loop of aluminium on a flat, rectangular board 11.5 by 7.5 cm and has a track spacing of 1 mm (Figure 2). The narrow track spacing means that the sensor can detect even the smallest amounts of moisture reaching the rock surface. The sensor responds to the presence of liquid water by recording conductivity and a zero value is given if there is either no moisture present or if the surface is frozen.

The sensors were attached to a Campbell CR10X datalogger and set to record hourly average readings at an execution interval of 20 seconds. At Gneiss Point and Terra Nova Bay the sensors were attached to the surface of the rock using small bolts and straps (Figure 2). However, this was not possible at Victoria Valley (due to problems with the drill) and strong glue was used. Despite the apparently precarious nature of the latter attachment, all sensors remained in place throughout the measurement season.

Sensor results were given in mV (a measure of conductivity) but were later converted to microlitres by establishing a relationship between quantity of moisture on the surface and the recorded mV in a controlled laboratory experiment. Increasing quantities of water were applied to the surface of a sensor using a 200ml Eppendorf micropipette. The water droplets were then spread out on the surface using a low absorbency paper napkin and the conductivity recorded on a Campbell CR10X datalogger. The measured relationship had a coefficient of determination of 95 percent.

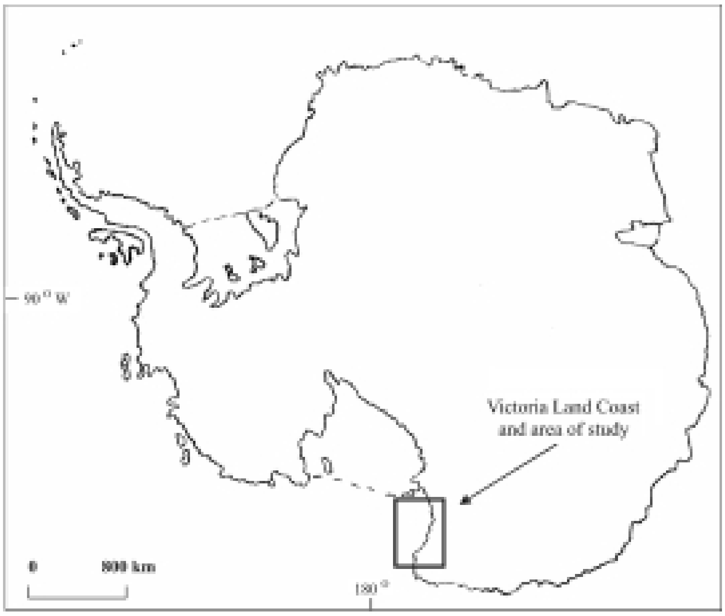

Figure 1: Antarctica, indicating the location of the field sites

Figure 2: Moisture sensor attached to rock surface at Terra Nova Bay

Results

A surface wetting event begins when the moisture sensor records a value greater than zero and ceases when the sensor measurement returns to zero again. The number of times that each rock surface was recorded as being wet is given in Table 1. Recordings were made over a different number of days at each location and the mean number of wettings per day has been calculated to enable some comparison between sites to be made. These data indicate that, on average, the rock surfaces at Gneiss Point and Victoria Valley were wet every other day during the 2002/03 summer whereas at Terra Nova Bay they were wet every three to four days in the 2003/04 season, depending on aspect.

Figures 3, 4 and 5 show that surface wetting events differ in magnitude, timing and duration with both aspect and location. For example, the surface wetting events at the south-facing Gneiss Point site were relatively well spread out during the measurement period, whereas at the west-facing site 70 percent of the wetting events occurred in the latter part of the season (Figure 3). At Victoria Valley the north-facing site received greater levels of moisture than the horizontal one in the early part of the season but the opposite occurred in the latter part of the season (Figure 4).

An analysis of the duration of surface wetting events is given in Table 2. Surfaces are wetted between 16 percent (Terra Nova Bay south-facing site) and 39 percent (Terra Nova Bay west-facing site) of the time and the maximum duration of wetting ranges from two days at the Gneiss Point west-facing site to 12 days at the Terra Nova Bay west-facing one. However, whilst most surface wetting events are short (i.e. less than or equal to 8 hours) this varies from site to site. For example, the number of events of this duration ranged from just over half (52%) at the Victoria Valley horizontal site to approximately three quarters (76%) at the Gneiss Point south-facing one (Figure 6).

Discussion

According to Campbell and Claridge (1987) precipitation levels in the region of interest here are very low, with values ranging from approximately 45 to 188 mm water equivalent per annum. However, Goudie (1997) notes that, even though by definition deserts are areas of moisture deficit, moisture is available in a variety of forms including dew, fog in coastal areas and rainfall. Although the latter is not intense it does occur on a greater number of occasions than is often anticipated. For example, measurable rainfall ranged from one in every 20 days in the Khartoum Desert of Sudan to one in four or five days in the Turgaj of the former USSR.

Table 1: Number of surface wettings per day at each site

Site		Period of Recordings	No. of Days	No. of Surface Wettings	Mean Wettings per Day	Mean Interval of Surface Wettings (Days)
Gneiss Point	*S*	26/10/02 to 18/01/03	85	46	0.54	1.8
	W	26/10/02 to 18/01/03	85	41	0.48	2.1
Victoria Valley	*Horizontal*	30/10/02 to 25/01/03	88	46	0.52	1.9
	N	30/10/02 to 25/01/03	88	39	0.44	2.3
Terra Nova Bay	*S*	14/11/03 to 14/01/04	61	16	0.26	3.8
	W	14/11/03 to 14/01/04	61	23	0.38	2.7

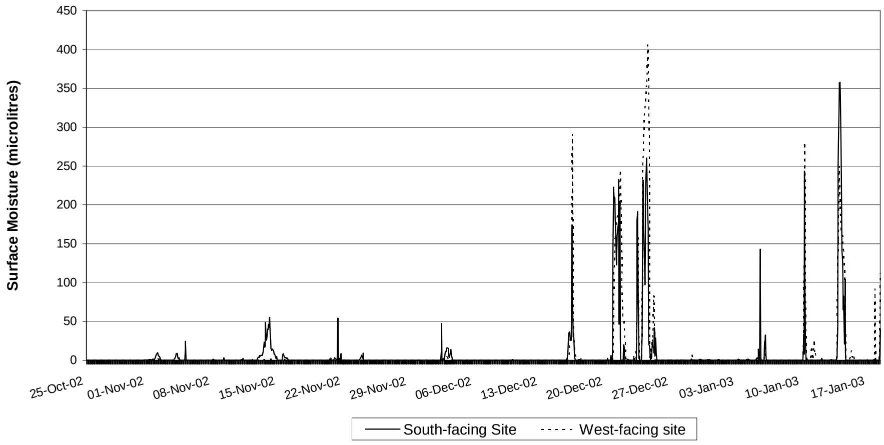

Figure 3: Surface moisture levels at Gneiss Point south- and west-facing sites

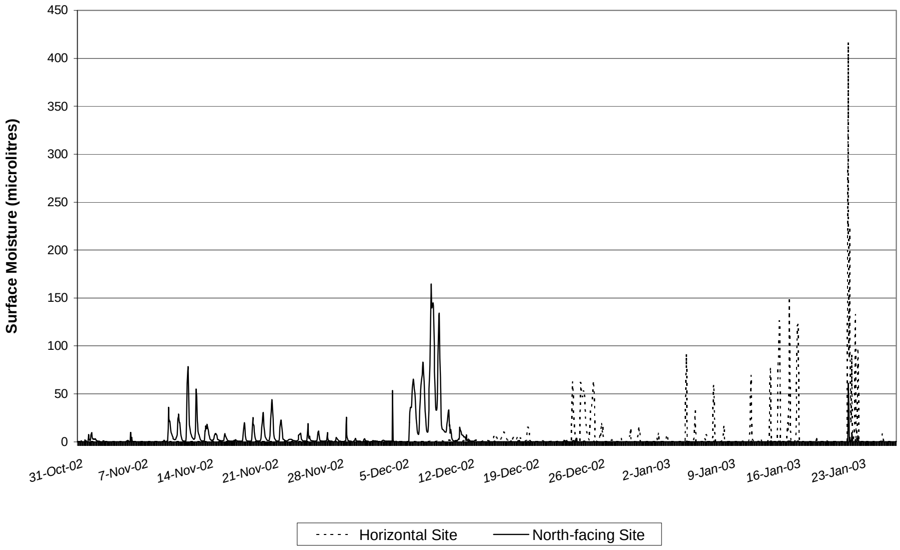

Figure 4: Surface moisture levels at Victoria Valley horizontal and north-facing sites

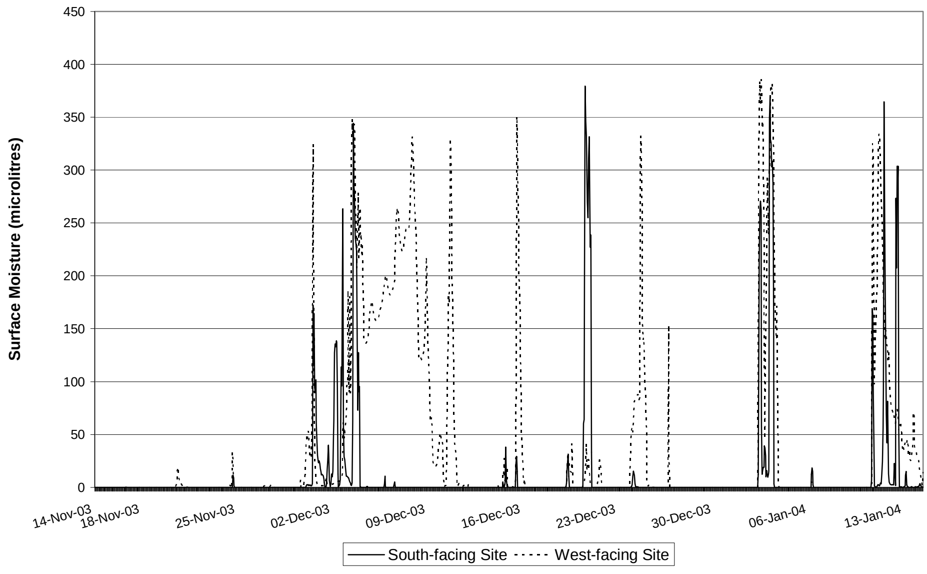

Figure 5: Surface moisture levels at Terra Nova Bay south- and west-facing sites

It is unlikely that fog or dew, as reported by Goudie (1997), are factors in providing moisture to the locations investigated here but the results from this study indicate that moisture, in the form of windblown snow (as opposed to new snowfall), may be more available to the surface of the rock than the precipitation levels noted by Campbell and Claridge (1987) imply. For instance, the frequency of surface wettings recorded at Terra Nova Bay in the summer of 2003/04 is similar to that found for rainfall in the Turgaj (Table 1).

One study from the Northern Hemisphere (Humlum, 1992) and two from Antarctica (Yoshikawa et al., 2000 and Friedmann et al., 1987) have investigated the frequency of moisture reaching the surface of rocks in cold climates. Friedmann et al. (1987) measured snow and rock humidity for just over two years at Linnaeus Terrace (77° 36' S; 161° 05' E) in the Asgaard Range, southern Victoria Land, Antarctica. They measured snowfall in a qualitative manner, recording it as either present or absent, and found a minimum of three snowfall events in each of the months of November and December of the study. This result was consistent with earlier studies (e.g. Koppen et al., 1981, cited in Friedmann et al., 1987), whereas Thompson et al. (1971), reported 62 snowfall events at Vanda Station in the Dry Valleys in 1969 but only eight in 1970.

An attempt was made to measure snowfall in this study but this was not successful (and none of the Automatic Weather Stations recorded precipitation). However, it is not precipitation *per se* that is important here but how often and for how long the surface is wetted. The proportion of time when the surface was wet due to new snow, as opposed to windblown snow, could be estimated by considering the

Table 2: Total number of wetted surface hours by site and location

	Aspect	Total Hours of recordings	Wetted Hours	Wetted hours as % of Total	Maximum Duration of Surface Wetting (days)
Gneiss Point	*S*	2035	368	18	2
	W	2035	336	17	2
Victoria Valley	*Horizontal*	2105	527	25	4
	N	2105	636	30	5
Terra Nova Bay	*S*	1462	230	16	4
	W	1462	568	39	12

number of hours when the surfaces at both aspects at a particular location were wet. This ranged from 6 percent at Victoria Valley to 11 percent at Gneiss Point indicating that, if numbers of new snow events are similar to these calculations or to the studies cited above, windblown snow may have as great, if not greater, influence than precipitation on rock weathering in these areas.

Yoshikawa et al. (2000) used a vertically mounted asbestos board to measure the frequency of snow collision in their study in the Ellsworth Mountains, Antarctica (80^{O} 21' S; 81^{O} 35'W). Although they did not publish any quantitative results, they noted that "Blowing snow and subsequent melting provided abundant moisture to the rock wall" (p575) and that moisture to the rock surface was supplied in summer by snow blown by katabatic winds rather than by snowfall. They also observed melting snow when snow was blown across a col, despite a mean air temperature of -17.2^{O}C.

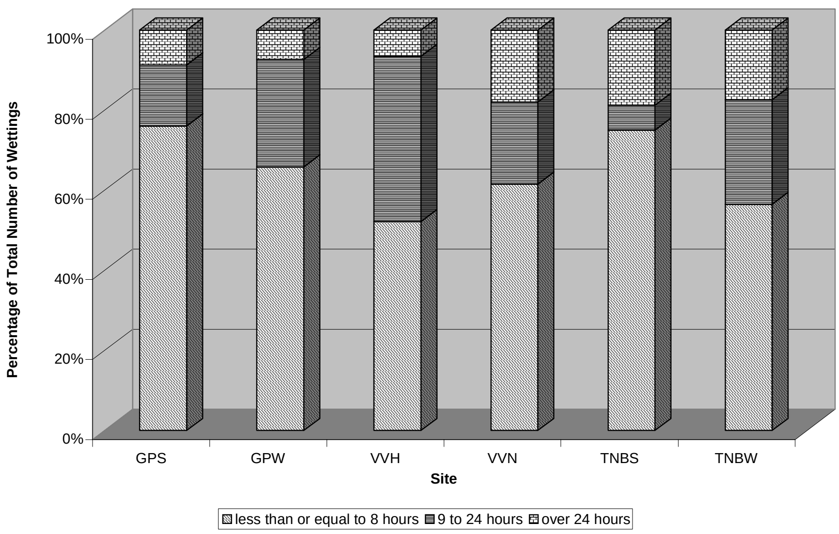

Figure 6: Proportions of surface wettings per day that were of short ($\leq$ 8 hours); medium (> 8 but < 24 hours) and long ($\geq$ 24 hours) duration

This finding of moisture and melting snow despite negative air temperatures was also reported by Humlum (1992) in his study in central West Greenland (69^{O} 15'N; 53^{O} 30'W) as well as in this study. For example, the average air temperature at the Victoria Valley north-facing site was –9.6 ^{O}C during periods when the surface of the rock became wetted. More interestingly the *rock surface* temperatures were also often below zero. For instance, the majority of occasions when this site was wet occurred in the early part of the season when the rock surface temperatures were almost always negative. The most extreme occasion occurred at 6.00 am on the 30th October when the rock surface was –23.3^{O}C; the air temperature –21.7 ^{O}C; the relative humidity 18 percent and an easterly wind was blowing at a speed of 0.6 ms^{-1}.

Yoshikawa et al. (2000) suggest that snow must be close to 0 ^{O}C before hitting the rock in order for it to melt and wet the surface making the air temperature more important than the rock temperature. Although Humlum (1992) did not measure rock surface temperatures he put forward three possible mechanisms to explain the melting of snow during times of negative air temperatures, and these may also help to explain the finding of surface wetness despite negative rock temperatures as experienced in this study. Firstly, snow particles may become crushed into small ice fragments by the collision with the rock surface with some becoming trapped within microscopic fractures or irregularities in the rock surface. The ice then turns into a liquid, possibly as a result of electro-molecular forces between the mineral surfaces and the water molecules (Tsytovich, 1975 and Gilpin, 1979 cited in Humlum, 1992) or solutes contained in the ice particles. A second possibility may be that solutes trapped within the rock are remobilised on saturation, lowering the freezing point (Hall, 1988), or thirdly, supercooled, unfrozen water droplets may be present in the air and get trapped by the rock surface on impact.

Humlum (1992) recorded weight changes in rock samples left in the field as well as precipitation, snowdrift and other climatic variables. Measuring changes in the weight of small rock blocks over time is a common field approach to estimating the quantity and variability of moisture in rocks. Humlum (1992) determined that 53 percent of observed variability in the weight of the rock samples was due to a combination of precipitation, relative humidity and cloud cover. He also found higher mean moisture content in the rock samples during the winter than summer, even though the temperatures were far below freezing. This implies that the summer moisture levels found in this study may be a minimum rather than a maximum as had initially been thought.

An examination of the climatic variables at each of the sites described here failed to find any consistent relationship between air temperature, rock surface temperature, wind speed and direction and times of surface wetting. For instance, a comparison of average wind speed and direction between the times when surfaces were wet at Gneiss Point and when they were dry indicated that wind direction was more important than wind speed. At the Victoria Valley on the other hand, the wind direction during wet and dry times was the same (ESE) but wind speeds were 5.4 and 4.1 ms^{-1} respectively, implying that wind speed was more important than wind direction in blowing snow onto these surfaces.

The choice of locations for this research was governed partly by availability of similar rock type and partly by a desire to get both a coastal/inland and a latitudinal perspective on moisture and weathering. It was anticipated that the coastal location of Gneiss Point would be wetter than the inland location of the Victoria Valley. However, there was little difference in the frequencies of surface wettings at these sites (Table 1). In addition, both Victoria Valley sites had a higher proportion of wetted surface hours than those at Gneiss Point (Table 2). However, there had been an uncharacteristic fall of snow at Victoria Valley in October 2002 which may have influenced these results. Nevertheless, this indicates that, at least on occasions, the rock surfaces at an inland site can be wet for longer periods than a coastal one at the same latitude.

Snow can be transported in one of three ways: by rolling or creep of dry particles within approximately 1 mm of the ground surface; by saltation or bouncing along the surface in a layer about 10 cm deep; or by suspension due to turbulent eddies lifting particles up to tens of metres above the surface (McClung & Schaerer, 1993). The greatest mass of windblown snow occurs just above the saltation layer i.e. at approximately 10 cm from the ground surface, and decreases with height at a rate that depends on wind speed (Pomeroy and Gray, 1995). However, for newly falling snow the majority of the mass is transported in the lowest metre above the surface (McClung and Schaerer, 1993).

The above implies that surface moisture as a result of either new snowfall or windblown snow will vary with height above ground. This may be one of the reasons why the Terra Nova Bay west-facing site had a much greater proportion of wetted hours than the south-facing one, whereas these were similar for both aspects at Gneiss Point (Table 2). The equipment at the two Gneiss Point sites was placed at similar heights, approximately 60 cm above the ground surface. However, at Terra Nova Bay the equipment at the two sites were at approximately 1 m and 50 cm above the ground surface for the south-facing and west-facing sites respectively and the latter was buried in snowdrift on return to the site in January 2004.

Implications for cold climate weathering studies

The results of this study, together with those of Humlum (1992) and Yoshikawa et al. (2000), have several implications for rock weathering research in cold climates. It has been argued that low moisture availability and low temperatures mean that chemical and biological weathering are largely absent in Antarctica (Campbell and Claridge, 1987) or occur only under locally favourable conditions (Hall, 1993b). However, the results from Victoria Land suggest that in practice more moisture is available, at least to the rock surface, than might be anticipated from an examination of precipitation patterns alone. The presence of clay minerals in the outer few millimetres of the surface in some of the samples from the Victoria Valley also support the possibility that chemical weathering might be more widespread than was previously thought, although it should be noted that these surfaces might have been exposed for significant periods of time. The possibility of chemical weathering even during winter is raised by Hall (2004) who found rock temperatures of up to 28 ^{O}C and evidence of water (as determined by the presence of exotherms in the temperature data) in his experiments in northern Canada. High rock surface temperatures were also experienced in this study and ranged from a maximum of 16.6 ^{O}C in the Victoria Valley to 27.7 ^{O}C at Terra Nova Bay.

There has also been ongoing debate about whether there is sufficient moisture available for freeze-thaw weathering to take place in many Antarctic environments (e.g. Matsuoka et al., 1996). The frequencies and duration of surface moisture recorded in this study as a result of blowing snow imply that there is at least the potential for moisture to permeate into the rock and that, provided there is also an appropriate temperature regime, freeze-thaw weathering may occur more widely than has previously been proposed. However, Hall (2004) challenges the usual definition of freeze-thaw weathering as occurring when a particular temperature (e.g. 0 ^{O}C) or temperature range (e.g. ± 2 ^{O}C) is crossed and provides evidence to indicate that the temperature at which the moisture in rocks freezes varies depending on aspect, slope and time of day.

Hall (1993a) suggests that frequent wetting and drying of rock can, by itself, promote rock breakdown and others (e.g.

Fahey and Dagesse, 1984) suggest that hydration shattering may also have a role, either independently, or in conjunction with freeze-thaw weathering. The frequency with which the rock surface is moist in this study supports the possibility of the former and the presence of clay minerals, a requirement of hydration shattering, in the surface of some rocks may support the latter.

This paper has focused on the availability of moisture in rock weathering research. However, Hall and Andre (2001, 2003) and Hall et al. (2002) argue that thermal stress fatigue, due to repeated heating and cooling, or thermal shock as a result of rapid temperature change, in the absence of moisture, may play an important role in rock weathering, producing granular disintegration and fracturing respectively. Certainly there is plenty of evidence of both grus and fractured rocks at all four locations investigated here (Figure 7). Data collected in this study indicate that there were a maximum of four occasions per day when the generally accepted threshold of 2 ^{O}C min^{-1} for thermal shock to take place occurred, but it is not known if this frequency is sufficient in itself to promote weathering by thermal shock. However, Hall and Andre (2003) also argue that many potential occasions when the temperature gradient is greater than 2 ^{O}C min^{-1} are missed unless high frequency (e.g. 20 s intervals) and high sensitivity (e.g. = 0.15 mm in diameter) thermocouples are used. The addition of some moisture may increase the effectiveness of this process (Griggs, 1936) and this will also be investigated in the laboratory experiments.

Figure 7: Evidence of granular disintegration and fracturing at Gneiss Point

Conclusion

Despite the low estimates of precipitation in this part of Antarctica, evidence from measurements undertaken during two summer seasons indicate that blowing snow frequently provides moisture to the surface of the rock. This happens even during periods of negative air and rock surface temperatures and can result in the rock surface being wetted for up to 40 percent of the time. This implies that, even in the very cold, dry climates under consideration here, a number of weathering processes deemed not to operate due to lack of moisture may indeed occur.

Further work

Better knowledge of the moisture regimes in a variety of cold climate environments is required to develop an increased understanding of the availability of moisture for rock weathering. In addition, understanding what happens to that moisture and how it moves within the rock also needs to be investigated. Measurements of the quantities of moisture at 45 mm and 90 mm depth in the rock, as well as surface and subsurface rock temperatures, were made as part of this study and will be the subject of a further paper. The effect of moisture on the weathering processes that operate, together with the rate of weathering, also need to be understood and these will be investigated in the laboratory using rock surface temperatures and levels of moisture found in the field. This will include examination of the effects of thermal shock and thermal fatigue.

Acknowledgements

Grateful thanks to my supervisors; Ian Owens, Barry Fahey, Bryan Storey and to Justin Harrison, Jordy Hendrikx, Hilary Cave, Ian Owens, Angelique Prick, Yvonne Cook and Rob McBrearty for their help and support in the field at various times. Also to the Department of Geography and Gateway Antarctica at the University of Canterbury and to Antarctica New Zealand for their financial, logistical and other support and to Nick Key of the Department of Geography for the many inventions that helped to support us in the field. I am also extremely grateful to the Arctic and Alpine Research Center at the University of Colorado and the Antarctic Meteorological Center at the University of Madison-Wisconsin for access to their meteorological data. My appreciation goes also to the Italian Antarctic Programme for their patience, support and hospitality during the time spent at Terra Nova Bay. Finally, thanks to the anonymous reviewers whose comments have significantly strengthened the paper.

Notes

[1] The amount of heat absorbed (or released) by unit mass of a system for a corresponding temperature rise (or fall) of 1 degree (Oke, 1987).

[2] In this context the term moisture is used to refer to water in either its liquid or vapour states

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